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Effects of Subsidence from Thick Seam Coal Mining on Hydrology

Hittman Associates, Inc.
Englewood, CO

Prepared for

Bureau of Mines
Washington, D.C.

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EFFECTS OF SUBSIDENCE FROM THICK SEAM COAL MINING ON HYDROLOGY

Prepared for

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

by

HITTMAN ASSOCIATES, INC.
Woodside Plaza I, Suite 122
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Englewood, Colorado 80111

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The Bureau of Mines contracted a study to estimate what effects the underground mining of thick coal seams in the Western United States would have on the surrounding water resources. Potential coal fields in the Western United States where this type of mining might occur were identified. Foreign literature was searched for studies of effects on hydrology from thick seam underground coal mining. Based on the limited information obtained from the literature, estimates of the effects of this type of mining on the ground and surface water in the Western States were made.

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FOREWORD

This report was prepared by Hittman Associates, Inc., Englewood, Colorado, under USBM Contract number J0295012. The contract was initiated under the Minerals Environmental Technology Program. It was administered under the technical direction of the Denver Mining Research Center with Richard Oitto acting as Technical Project Officer. Larry Rock was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period July, 1979 to March, 1980. This report was submitted by the authors on March 7, 1980.

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EFFECTS OF SUBSIDENCE FROM THICK SEAM COAL MINING ON HYDROLOGY

by

Richard C. Moore[1] and Michael A. Nawrocki[2]

ABSTRACT

The U.S. Bureau of Mines contracted a study to estimate what effects the underground mining of thick coal seams in the western United States would have on the surrounding water resources. Potential coal fields in the western United States where this type of mining might occur were identified. The foreign literature was searched for studies of effects on hydrology from thick seam underground coal mining. Based on the limited information obtained from the foreign literature, estimates of the effects of this type of mining on the ground and surface water in the western states were made.

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SECTION 1

INTRODUCTION

Background

Coal is becoming an increasingly important energy source in the United States. Of the vast coal deposits present in the United States, approximately 54 percent occur west of the Mississippi River, and it is presently estimated that the majority of these western deposits can only be extracted by underground mining (1)[3]. Many of these underground mineable seams are also fairly thick (15 feet thick or greater).

Most methods presently being employed to underground mine thick coal seams in the United States have rather low recovery ratios, resulting in waste of a valuable resource. Consequently, the U.S. Bureau of Mines has sponsored studies of underground coal mining methods used in foreign countries to extract thick seams. These methods have a higher recovery ratio than the approximately 30 percent recovery of the coal which is achieved by underground methods presently used for mining thick coal seams in the United States. Through these studies, interest has been generated in four underground mining methods used in foreign countries. These methods are multislice longwalling, longwall caving, highface longwalling, and sublevel caving by pillar extraction. All of these methods maximize coal recovery by extracting the entire thickness of the coal seam over a large area and leaving no support pillars. For the sake of simplicity, these methods will be referred to as longwall or total extraction in this report.

The result of this maximized coal extraction would, naturally, be increased land surface subsidence. However, the effects of this subsidence on other aspects of the environment was not known. In the water-short western United States, where many of the underground mineable thick coal seams are located, it is especially important to determine the effects of the subsidence on the surrounding water resources.

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[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Project Objective

This study was initiated to try to estimate the severity and duration of any impacts to the ground and surface water hydrology which might be caused by utilization of these high recovery ratio mining techniques on thick coal seams in the western United States. This basic objective was accomplished through:

(1) Identifying coal seams greater than 15 feet thick in the western United States that require underground mining and underlie significant ground and surface water resources;

(2) reviewing any studies in the foreign literature which monitored or analyzed the effects of underground thick seam coal mining on the hydrology; and

(3) applying what was learned from the foreign case histories to estimate the hydrologic impacts from underground thick seam coal mining in the western United States.

Project Methodology

This project focused on the western states of Montana, Wyoming, Colorado, New Mexico, Idaho, Utah, and Arizona. It was designed to determine the order of magnitude of the problem, which included discovering whether any previous studies investigated the problem; analyzing the results of these studies; determining if there was a perceived problem and, if so, defining the magnitude of the effects; and finally, making recommendations for further investigations, if warranted. Information needs for the study were met by existing literature and data. No new field measurements were taken as part of this project. The major work items in this study are discussed below.

Identification of Thick Coal Seams

Within the seven western states, the available literature and data were reviewed to identify coal fields that:

(1) Have seams greater than 15 feet in thickness;

(2) require underground mining; and

(3) underlie significant (i.e. having economic and/or ecologic value) ground and/or surface water sources.

Information obtained about coal fields meeting these criteria included their name and location; location, areal extent, and thickness of thick mineable coal seams; geologic, topographic, and physical characteristics; mining conditions; potential pollution problems; and significant ground and surface water sources.

Foreign Case Histories

The foreign literature was searched for case histories in which the effects of subsidence on the surrounding ground and surface water resources were studied. It was attempted to obtain case histories from the foreign literature which included both of the following conditions:

(1) Total extraction of thick coal seams and consequent land subsidence; and

(2) an analysis of the effects on hydrology due to the subsidence.

Throughout the course of this study, no foreign case histories were found which directly addressed both of these points. Consequently, the literature review was expanded to include some studies from within the United States and some studies which indirectly provided data pertinent to the problem. All pertinent information and data were accumulated and assessed for use in predicting hydrologic impacts.

Assessment of Hydrologic Impacts in the Western United States

Using the information gathered on western coal seams, ten potential thick seam underground coal mining areas in the western United States were selected. The areas selected represented a variety of hydrologic, geologic, climatic, and geomorphic conditions. The information gathered during the literature review was then used to estimate the impacts from extraction of the thick coal seams on the ground and surface water flow, quantity, and quality. Legal aspects, in terms of water rights, of the anticipated hydrologic impacts were also studied.

SECTION II

IDENTIFICATION OF THICK COAL SEAMS

Purpose

One of the objectives of this study was to identify those coal fields in the western United States which meet the following criteria:

(1) Contain seams mineable by total extraction methods and which have thicknesses greater than 15 feet;

(2) contain thick seams which at least in part require underground mining;

(3) contain economically or ecologically significant ground and/or surface water resources which may be disrupted by the subsidence associated with the total underground extraction of thick coal seams.

For this study, the western United States is defined as Montana, Wyoming, Colorado, New Mexico and the contiguous states west of them, that is, Idaho, Utah, and Arizona. For each identified coal field, to the extent possible, the following information was obtained:

(1) Name and location;

(2) location, areal extent, and thickness of mineable coal seams greater than 15 feet thick within the fields;

(3) geologic structure, lithology, and topography;

(4) mining conditions;

(5) potential toxic and acid-forming materials in the seam and overburden; and

(6) significant ground and surface water resources.

Methodology

No field work was performed during this study. Data on the coal fields were acquired from published studies, maps, records, contact with appropriate local, state and federal agencies, and personal communications. Some of the more prominent sources of information were U.S. Geological Survey circulars, maps, and bulletins. The U.S.G.S. has published a bulletin for nearly every coal field in the western United States. Many of these, however, are outdated and provide minimal information. U.S. Bureau of Mines publications were also found to be helpful. Environmental impact statements and other environmental assessments required by federal and state regulations were also exploited. State agencies have produced many publications which delineate coal resources. The most notable of these is the Coal Monograph Series compiled by the Utah Geological and Mineralogical Survey (2). This series provided significant information in an organized format and was accompanied by useful maps, charts and tables. Data compiled by coal and mining companies were used where possible. Much of this private mining company information however, pertains to a very concentrated portion of a particular coal field. In addition, these data from the private sector were not readily accessible, and acquisition of this information was somewhat limited by the study constraints.

In some instances, the available data did not permit a thorough evaluation of the coal field. For instance, in the case of some coal fields, evidence of thick seams was garnered from a few widely spaced drill holes. This made it difficult to determine whether seams were uniform enough in thickness and of a large enough aerial extent to make them economically feasible for mining. Other factors which might limit mineability such as the presence of splits (thin interbedded layers of shale or other noncoal material), faulting, and local changes in dip were also difficult to assess due to data deficiencies. Thus in many instances, the mineability of thick seams became a subjective judgement. Generally, if a field showed evidence of a thick seam, it was considered mineable unless there was definite data to the contrary.

Whether or not significant water resources were present in or near a field had to be considered in the context of the high value placed on any water resources in the arid to semiarid western United States. If water resources were measured by eastern standards, few western coal fields would have qualified. Therefore, unless fields were shown to contain no useable water resources, they were not eliminated by this criterion.

Results

The states containing the largest thick coal seam resources were Montana and Wyoming. While much of the coal in these two states is mineable by surface techniques, much of it will also have to be exploited by underground methods given present day technology and economics. As would be expected, the bulk of the information available for Montana and Wyoming fields pertains to that coal which is strippable.

Colorado and Utah also contain significant thick coal resources. For these two states, especially Utah, underground mining techniques will probably become more important in the near future owing to thick overburden and the presence of topographic barriers to surface mining.

New Mexico contains large amounts of coal but few thick seams. The San Juan basin contains the bulk of New Mexico coal with the few identified thick seams being concentrated in the northwestern portion of the state. A projection of outcrop and drill-hole data into the deeper portions of the basin indicates a good possibility that more thick coal exists which up to now has not been identified.

No fields containing mineable thick seams were identified in Idaho or Arizona. The thickest coal beds in Idaho are reported by Kiilsgaard (3) to occur in a 14-foot seam at the Idaho Mine in the Horseshoe Creek District of eastern Idaho. The Black Mesa Field in Arizona showed evidence of one or two very lenticular, localized seams in excess of fifteen feet, but available data did not permit including it amoung the thick-seam fields.

Descriptions of each of the fields found to meet the above mentioned criteria are organized by state in Appendix A.

SECTION III

FOREIGN LITERATURE SEARCH

Purpose

Since underground thick seam coal mining technology has been utilized in foreign countries for a number of years, the foreign literature was searched to determine if any of this type of mining's effects on the surrounding water resources has been studied. It was hoped that if studies of this type could be found, the results could be used to estimate the effects which might occur in similar areas of the western United States.

Methodology

The search for foreign literature in the subject area was performed utilizing compilations of abstracts, computerized literature searches, in-house literature, and libraries of government agencies. An abstract of every promising article was obtained and, if the abstract proved interesting, a copy of the article was obtained and translated into English, if necessary.

The main noncomputerized abstract compilation which was used in the foreign literature search was Coal Abstracts, a publication of the International Energy Agency, Technical Information Service, located in London, England. Abstracts pertaining to the subject area under investigation were studied. Articles which were in some way related to the study at hand were obtained and reviewed. Pertinent information was then abstracted from them.

Two computerized literature searches were also utilized:

(1) The U.S. Department of Energy's RECOKEN, a computerized literature information file located in Oak Ridge, Tennessee; and

(2) a computerized literature search service provided by the Smithsonian Science Information Exchange, Inc., Washington, D.C.

The RECOKEN literature information file was searched using the following descriptors:

(1) thick coal seams,

(2) underground mining,

(3) longwall methods,

(4) subsidence, and

(5) hydrology.

The Smithsonian Science Information Exchange search was conducted on "Effects of Underground Mining of High Coal on Hydrology (Particularly Foreign)". Data processing requirements necessitate substituting "high coal" for "thick coal".

Additional information was obtained from a number of other sources, most notably, from a number of international symposiums on subsidence associated with underground coal mining and other activities.

Results

Appendix B contains a bibliography of all literature reviewed in connection with this study. Literature which was in some way related to this study from a total of 20 foreign countries was found and reviewed. These foreign countries are listed in table 1.

No one, complete case history which contained all the necessary ingredients, namely, subsidence from underground thick seam coal mining and its effects on hydrology, was found in the foreign literature. The closest which any foreign case histories came to meeting all these criteria were some studies in Great Britain, which dealt with some hydrologic impacts associated with the longwall mining of one to two-meter thick seams. Throughout the literature review, the most information was obtained on ground and surface water flow and quantity. Nothing substantive was found on the effects on water quality.

To supplement the foreign literature, a survey was also conducted of the United States literature on the subject. Additional information on the effects of subsidence on hydrology was found in the U.S. literature.

TABLE 1. - Foreign countries from which literature was reviewed

Australia

Canada

Peoples Republic of China

France

German Democratic Republic (East Germany)

Federal Republic of Germany (West Germany)

Great Britain

Hungary

India

Japan

New Zealand

Poland

Romania

South Africa

Spain

Sweden

Turkey

Union of Soviet Socialist Republics (Russia)

Yugoslavia

Zambia

SECTION IV

PREDICTION OF HYDROLOGIC IMPACTS

Subsidence Prediction

The best source of data from case histories of subsidence over longwall-type mines is the Subsidence Engineers' Handbook (4) published by the National Coal Board of Britain. The handbook presents a comprehensive method for predicting subsidence parameters based on empirical data from 165 case studies in British coalfields. The mines range from 80 to 2,730 feet mean depth, with seams from 2 to 18 feet thick, seam dips up to 25 degrees, panel widths from 120 to 1,968 feet, and width-depth ratios from 0.05 to 5.92. The conclusions and methodology contained in the manual are generally applicable to areas outside of the British coalfields. Care must be taken however, in applying them to areas where mine parameters fall outside of the range of data used to derive the manual. Consideration must also be given to differences in geologic conditions when using the manual to predict subsidence parameters for coal mines in strata other than the British Coal Measures. In order to assess the importance of these differences, case histories from other parts of the world were studied.

For the purpose of this study, subsidence is defined as the vertical movement of surface points within a subsidence trough above a longwall-mined coal seam. Subsidence is a three dimensional phenomenon but consideration of it can be simplified by viewing it in two dimensions. The two dimensional geometry of a subsidence trough is shown in figure 1, which illustrates a typical panel in plan view and in cross section perpendicular to the panel length. The symbols used in figure 1 and elsewhere in this report conform, for the most part, to those used by the British National Coal Board.

Subsidence geometry can be described by a few characteristic elements: (1) limit angle, (2) maximum subsidence, and (3) subsidence profile. The nature of these elements is determined by a number of variables. The most important of these variables are dealt with in the following discussion.

Limit Angle

Angle ζ in figure 1 is termed the draw or limit angle. It is defined as the angle of inclination from the vertical of the

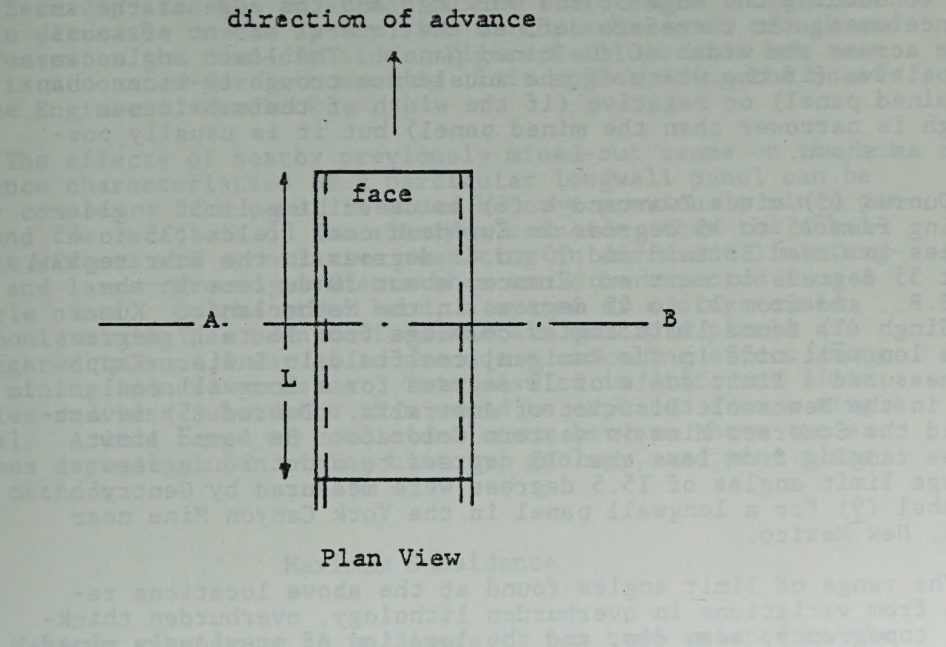


FIGURE 1. - Typical longwall panel with subsidence trough.

line connecting the edge of the workings and the edge of the subsidence area. It therefore defines the lateral extent of subsidence across the width of the mined panel. The limit angle can be positive (if the width of the subsidence trough is wider than the mined panel) or negative (if the width of the subsidence trough is narrower than the mined panel) but it is usually positive as shown.

Dunrud (5) cites Zwartendyk (6) as describing limit angles ranging from 25 to 45 degrees in European coal fields (35 to 45 degrees in Great Britain and 30 to 45 degrees in the Ruhr region), about 35 degrees in northern France, about 30 degrees in the U.S.S.R., and from 35 to 45 degrees in the Netherlands. Kumar and Singh (7) found limit angles to range from 16 to 17 degrees for a longwall mine in the Raniganj coalfield in India. Kapp (8) measured a limit angle of 38 degrees for a longwall coal mine in the Newcastle District of Australia. Dunrud (5) investigated the Somerset Mine in western Colorado. He found limit angles ranging from less than 15 degrees to about 20 degrees. Average limit angles of 15.5 degrees were measured by Gentry and Abel (9) for a longwall panel in the York Canyon Mine near Raton, New Mexico.

The range of limit angles found at the above locations results from variations in overburden lithology, overburden thickness, topography, seam dip, and the location of previously mined out areas.

The primary variable is overburden lithology. The relationship is an inverse one in that the limit angle decreases as the strength of the overburden increases. Gentry and Abel (9) found that subsidence over panel 4N at the York Canyon Mine exhibited limit angles less than those predicted using the Subsidence Engineers' Handbook. They attributed the difference to the presence of thick, strong, sandstone beds. The lower limit angle values measured by Kumar and Singh (7) in India were also associated with hard sandstone in the overburden. Mohr (10) studied the Ruhr coal field of West Germany. Limit angles there were smaller in strong rocks having large angles of internal friction and increased in weak rocks having small angles of internal friction.

Dunrud (5) found a possible correlation between limit angle and overburden thickness at the Somerset Mine. There, the limit angle decreased as overburden thickness increased. This finding was complicated somewhat by varying degrees of rock strength.

At the York Canyon Mine, Gentry and Abel (9) concluded that the limit angles were also affected by variations in topography. They tended to decrease under topographic lows or where the topography sloped away from the center of the trough.

Seam dip also has an effect on the limit angle. The limit angle decreases on the up-dip side of the subsidence trough and increases on the down-dip side. Figure 2 illustrates how seam dip is accounted-for in computing limit angles using the Subsidence Engineers' Handbook.

The effects of nearby previously mined-out seams on the subsidence characteristics of a particular longwall panel can be very complex. If a panel is mined below a previously mined panel and the locations of the ribsides coincide, then the subsidence effects are cummulative resulting in different limit angles and larger ground movements than would be expected from a single panel. On the other hand, a system of mining termed harmonic mining has been devised wherein multiple panels are staggered in such a way as to produce a canceling effect among the mining induced stresses. This results in different limit angles and less subsidence than would be expected from a single panel. A wide range of conditions occur between these two extremes depending upon mining history, geology, and mine plans and methods.

Maximum Subsidence

Maximum subsidence (S in figure 1) has been related to the width of the panel, w, seam depth, h, and the mined seam thickness, m, in figure 3 from the Subsidence Engineers' Handbook. The graph uses panel width and overburden depth to predict maximum subsidence expressed as a proportion, S/m, of the mined seam thickness. Consequently, S = xm where x is a constant of proportionality sometimes called the subsidence factor. For a given value of m, S becomes a function of x. The optimum combination of width and depth (normally expressed as the width-depth ratio, w/h) will produce the highest achievable value of x (.9 for the conditions present in British coalfields) and maximum subsidence, S, will become equal to maximum possible subsidence, S_m. For a given depth, the width which causes S to equal S_m at one point on the subsidence trough cross section is termed the critical width (figure 4B). Panel widths for which $S < S_m$ are termed subcritical (figure 4A). When the panel width exceeds the critical value it is termed supercritical and the trough bottom flattens out at S_m (figure 4C). Wardell (11) notes that for European coal fields as a whole the width becomes critical when w/h is between 1.0 and 1.4.

Since the curves in figure 3 were developed from case histories of mines in the coal measures of Britain, they are subject to the limitations imposed by the range of data available. Limiting conditions specified in the Subsidence Engineer's Handbook are:

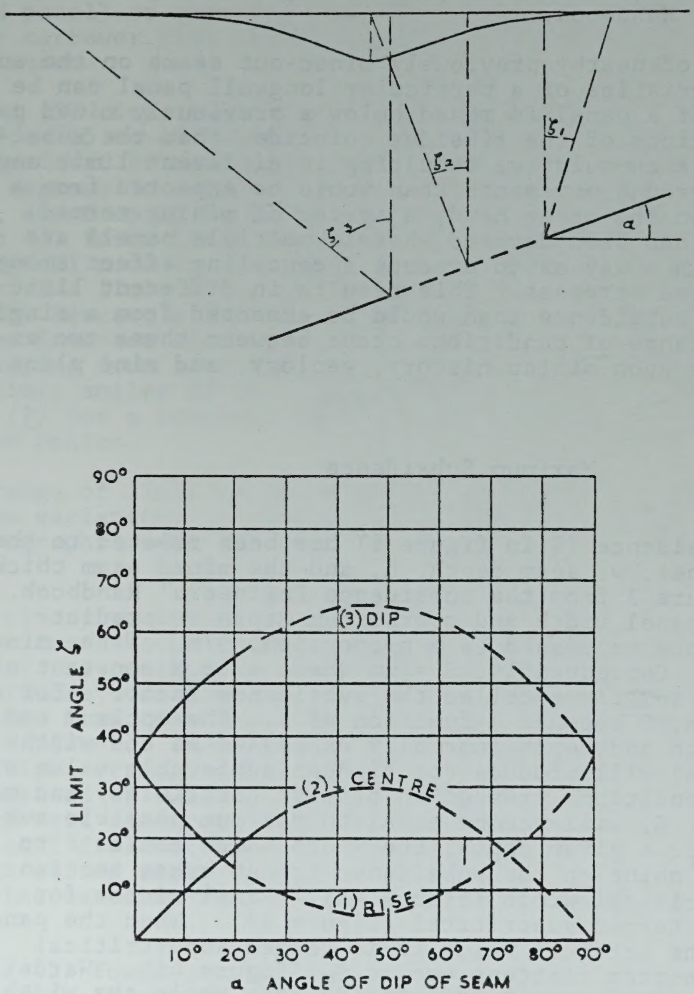


FIGURE 2. - Limit angle versus seam dip (4).

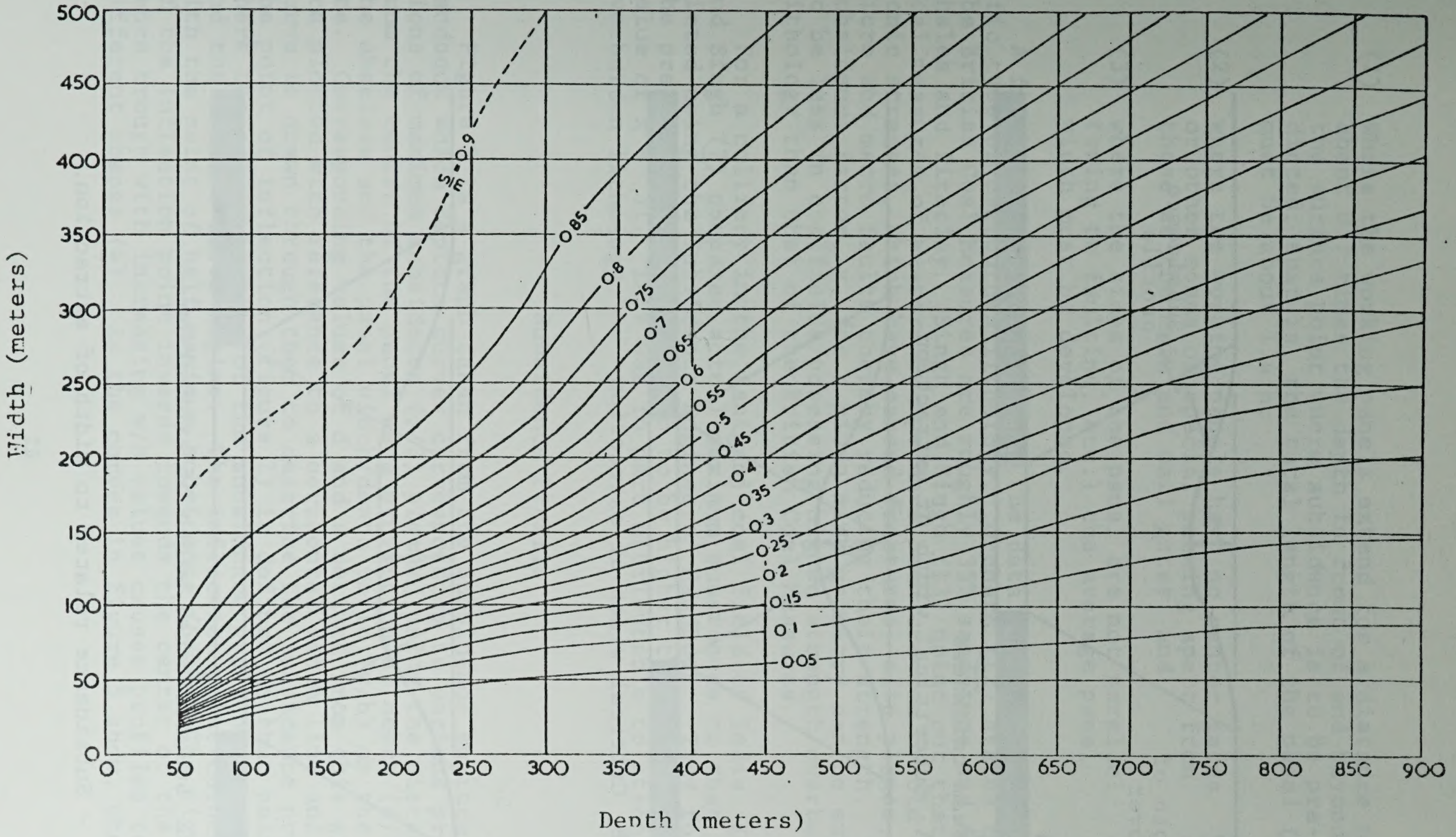
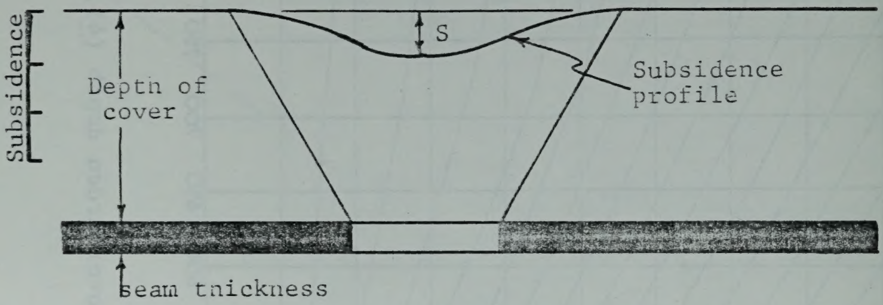
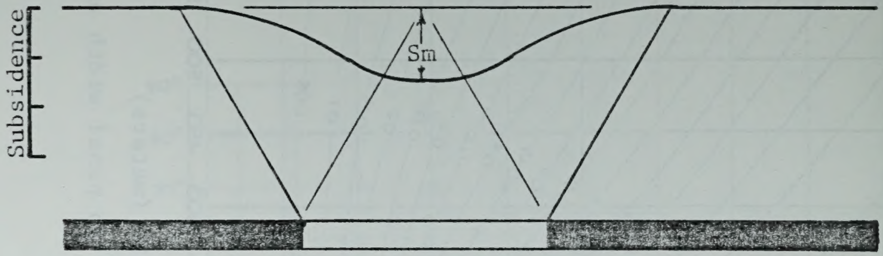


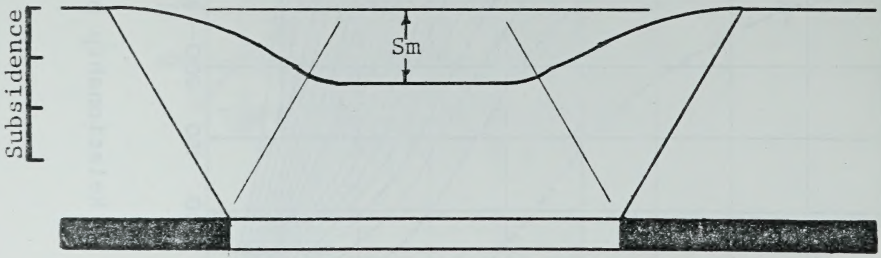
FIGURE 3. - Relationship of subsidence to panel width and overburden depth (4).



A. Subcritical width of extraction



B. Critical width of extraction



C. Supercritical width of extraction

FIGURE 4. - Subsidence related to width of extraction.

(1) Where the working panels extend for a distance of about 0.7 times the depth in front of and beyond the surface point where subsidence is to be predicted; that is, the total length of the panel (L) must be about 1.4 h;

(2) where the working panels have no center gates or other zones of special packing apart from those at the main and tail gates; and

(3) where the sides of the panel are not parallel (owing to faulting, etc.) the average panel width must be developed.

A further limitation is that the data pertains to a specific type of overburden lithology. Orchard (12) states that the British Coal Measures are roughly 35% sandstone and 60% shales and fireclay. Singh and Singh (13) point out that the coal measures of Western Europe have been cracked by old tectonic stresses, which have caused fractures, slip planes, and micro and macro faults thereby reducing their strength. The subsidence factor, x, for a given mine geometry can be expected to be less in coalfields posessing higher strength overburden lithology than that of the British Coal Measures.

For a colliery in the Raniganj coal field of India, Kumar and Singh (7) compared actual maximum subsidence to that predicted using the Subsidence Engineers' Handbook. They found the predicted value of x = .48 to be higher than the actual value of x = .31. This was in part attributable to stronger overburden lithology.

Subsidence Profile

Figure 5 is a graph taken from the Subsidence Engineers' Handbook which depicts curves corresponding to various proportions of maximum subsidence (s/S) plotted using the distance (d) from the center of the panel as a proportion of depth (d/h) on the abscissa and the panel width/depth ratio (w/h) on the ordinate. Corresponding values of d and s derived from this graph are plotted with reference to a horizontal datum line and a curve is drawn through them to describe the subsidence profile. The point of inflection (figure 1) is defined as that point where the convex portion of the subsidence profile curve ends and the concave curve begins. The inflection point coincides with the point of half maximum subsidence (S/2). The migration of the inflection point inwards towards the center of the subsidence trough with increasing w/h values causes profiles to be of different shapes (4). As the curves in figure 5 show, when w/h

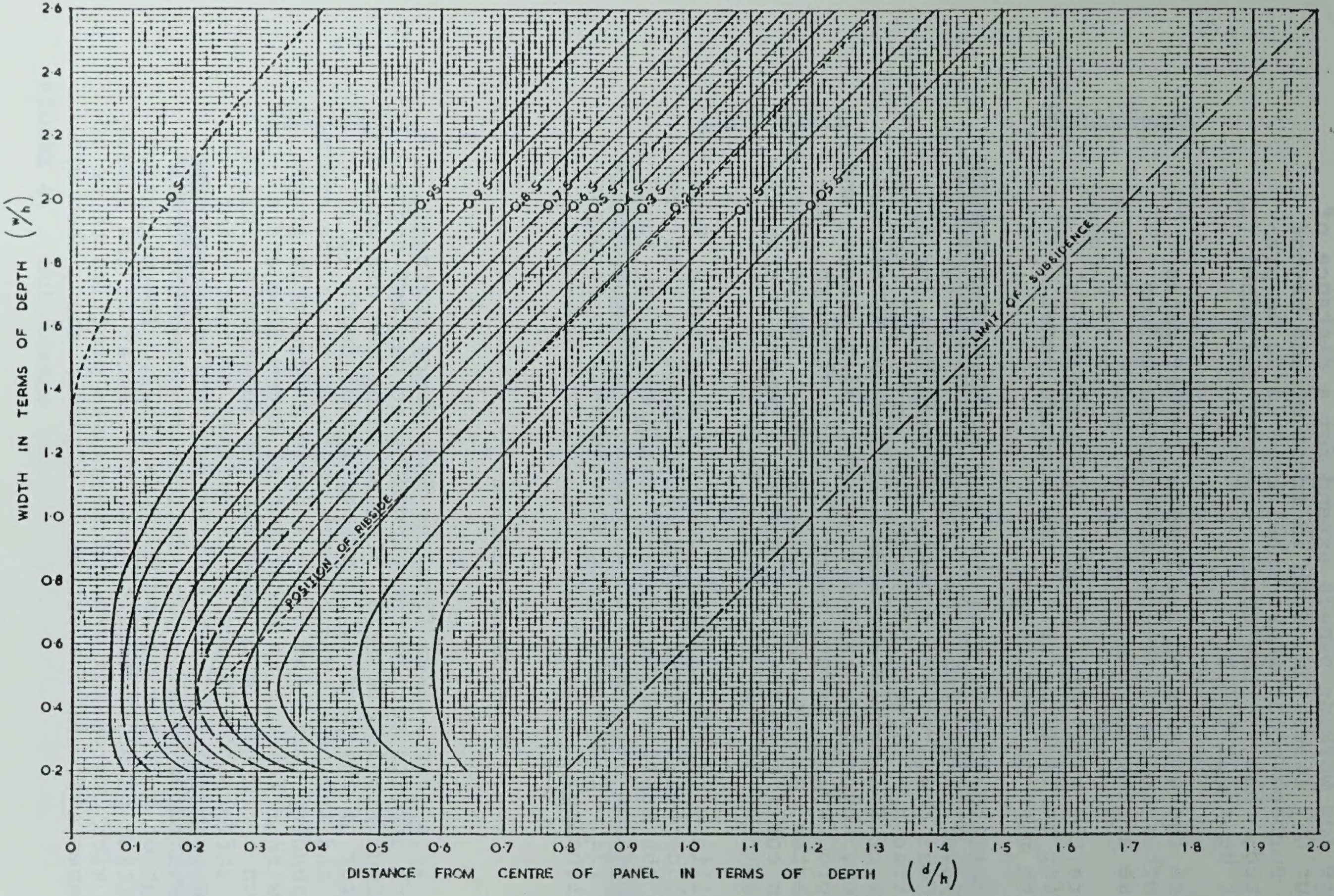


FIGURE 5. - Graph for predicting subsidence profiles (4).

is small, the inflection point (defined by the 0.5 S curve) is well outside the panel ribside and profile curvature is small in comparison to higher values of w/h where the inflection point is inside the ribside. Once w/h reaches the critical value (critical width), profile curvature remains constant with increasing w.

Once again, the curves in figure 5 were derived using data from the British Coal Measures and so are most appropriate for that particular type of overburden lithology. Kumar and Singh (7) compared observed subsidence profiles over coal mines in India to profiles predicted using the Subsidence Engineers' Handbook. The overburden above the Indian mines was characterized by high strength massive sandstone layers. They found generally that the observed profiles had less curvature than the predicted. As a result, they developed a series of equations for the purpose of predicting subsidence parameters under Indian conditions. For the prediction of a subsidence profile Kumar and Singh use the following equation:

$$s = S_m \; 1\left[- \frac{d^2}{D^2}\right]^2 \qquad (1)$$

where s = subsidence,
Sm = maximum subsidence,
d = distance of surface point from the center of the panel,
and D = distance of the point of zero subsidence from the center of the panel.

Gentry and Abel (9) noted significant topographic effects on subsidence profiles at the York Canyon Mine in New Mexico. The rugged, mountainous topography there differs markedly from the flat or gently rolling terrain associated with the British Coal Measures. In comparing predicted subsidence values using the Subsidence Engineers' Handbook to observed values, they conclude: "Predicted subsidence over ridge tops was 17 percent to 21 percent greater than actually measured. Predicted subsidence in topographic lows was approximately 55 percent greater than that measured".

Summary of Subsidence Prediction

The tables, graphs, and diagrams found in the Subsidence Engineers' Handbook constitute one of the most commonly used methods for the prediction of subsidence. The handbook is used to predict subsidence in this study. Care is taken however, not to strictly apply subsidence prediction techniques outside of the range of data used to derive them. The data used in the Subsidence Engineers' Handbook came from studies of mines in the coal fields of Great Britain. Overburden strengths of the British Coal Measures can generally be considered to be relatively low due to previous fracturing, the lack of massive sandstones, and the presence of large amounts of weaker, argillaceous rocks. Use of the Subsidence Engineers' Handbook can therefore be considered to be a conservative approach in that subsidence predictions for a given mining geometry will be maximized by basing them on empirical data from areas of weak overburden lithology. The strata in many western coal fields contain massive sandstone layers which results in overburden strengths exceeding those of the British Coal Measures. Therefore, the equation developed by Kumar and Singh (7) as well as the findings of other researchers are used in conjunction with the Subsidence Engineers' Handbook to provide a range of possible subsidence. Due consideration is also given to differing topography or other site specific characteristics not covered by the British data.

Subsidence in the hypothetical longwall mines in this study is predicted first for the start of mining, which is the initial longwall panel at each site, and then for the completion of mining, which is several adjacent panels whose combined dimensions total one square mile. The initial panel is in virgin coal and the subsidence profile over the central portion of the panel is assumed representative of the whole length of the panel, with the exception of the panel ends. For the plurality of panels the assumption is that no support pillars are left between panels and maximum subsidence occurs across the square mile mined because the critical width of extraction (figure 4c) is exceeded. The extraction distance both across and along the panels is one mile.

Surface Water Impacts

Impacts on surface water flow result from subsidence-induced changes in the configuration of the ground surface. Changes to the ground surface configuration can, in turn, lead to alterations in surface water quality by increasing or decreasing rates of erosion and/or deposition.

Impacts on Surface Water Flow

Surface water flow characteristics are impacted by subsidence in three primary ways: (1) vertical settlement of the surface, (2) local changes in surface slope, and (3) the opening of surface fissures in areas of high tensile strain. Amounts of vertical subsidence and changes in surface slope can be calculated from the subsidence profile. Amount and distribution of strain is a function of panel width, overburden depth, extracted seam thickness, premining surface gradient, and seam dip.

Vertical Settlement

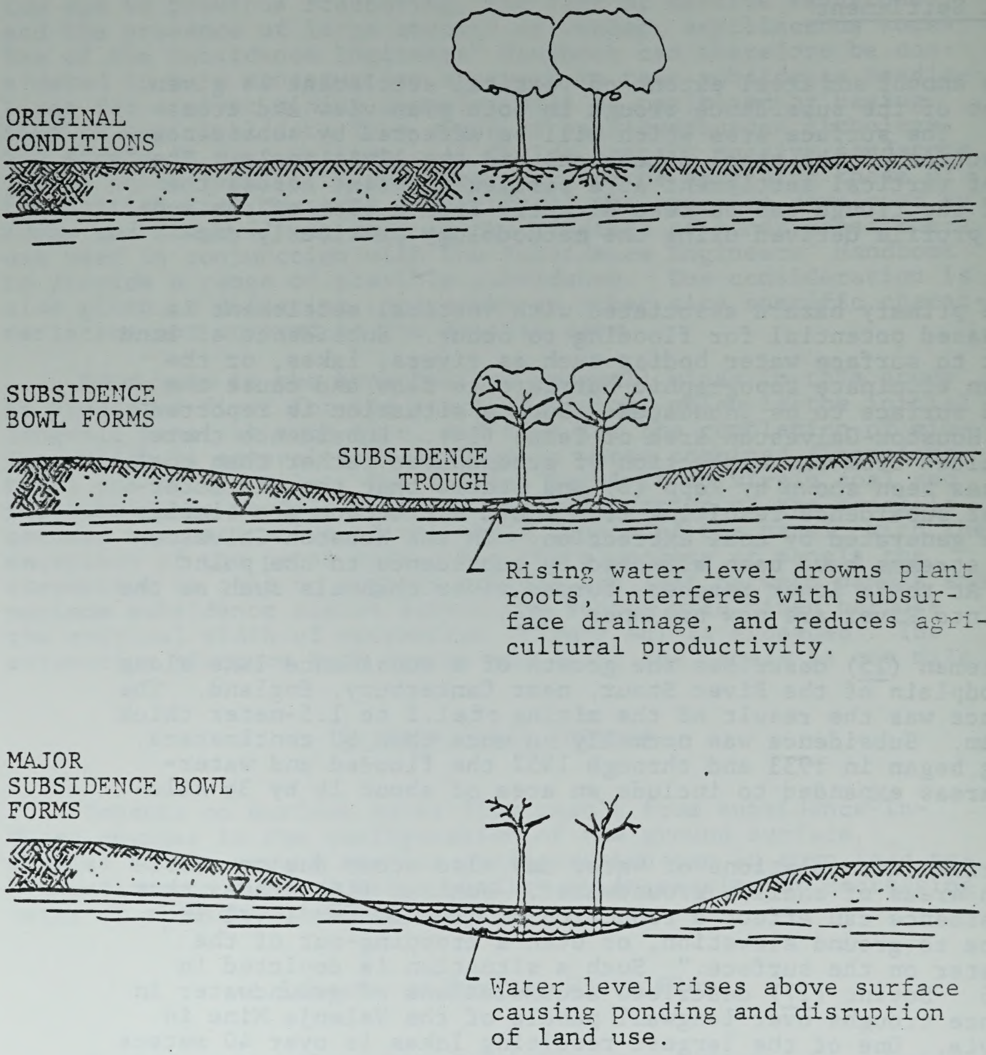
The amount and areal extent of vertical settlement is given by a plot of the subsidence trough in both plan view and cross section. The surface area which will be affected by subsidence is a function of the panel dimensions and the limit angle. The amount of vertical settlement at a particular point across the width of the trough can be read directly from a plot of the subsidence profile derived using the methodology previously described.

The primary hazard associated with vertical settlement is an increased potential for flooding to occur. Subsidence of land adjacent to surface water bodies such as rivers, lakes, or the ocean can eliminate topographic barriers to flow and cause the subsided surface to be inundated. Such a situation is reported for the Houston-Galveston area of Texas (14). Subsidence there has resulted from the extraction of groundwater rather than coal, but it has been shown by Kapp (8) and others that the characteristics of subsidence resulting from fluid extraction are similar to those generated by coal extraction. In the Houston-Galveston region, streams have been affected by subsidence to the point where, "At their lower reaches, former river channels such as the San Jacinto River are now baylands" (14).

Coleman (15) describes the growth of a subsidence lake along the floodplain of the River Stour, near Canterbury, England. The subsidence was the result of the mining of a 1.2 to 1.5-meter thick coal seam. Subsidence was normally no more than 60 centimeters. Flooding began in 1933 and through 1952 the flooded and waterlogged areas expanded to include an area of about 1¼ by 3½ kilometers.

Surface accumulations of water may also occur due to subsidence in areas of shallow groundwater. Wohlrab (16) states that, "...subsidence can effect a reduction of groundwater level in reference to ground elevation, or even a cropping-out of the groundwater on the surface." Such a situation is depicted in figure 6. Sovinc (17) describes accumulations of groundwater in subsidence troughs over longwall panels of the Valenje Mine in Yugoslavia. One of the largest resulting lakes is over 40 meters deep.

Vertical settlement can also have a negative effect on any hydraulic system, natural or man-made, which depends upon elevation differences and gravity flow. Irrigated fields, canals, sewers or natural streams which traverse subsidence troughs are disrupted by sudden changes in surface elevation.



Rising water level drowns plant roots, interferes with subsurface drainage, and reduces agricultural productivity.

Water level rises above surface causing ponding and disruption of land use.

FIGURE 6.- Effects of subsidence in shallow groundwater areas (14).

Surface Slope Changes

The amount of curvature in the subsidence profile determines the slope to be anticipated over a certain portion of it. The slope is calculated by dividing the difference in subsidence at two points on the profile by the horizontal distance between them. If two points A and B are located on a sloping portion of the subsidence profile, a is the amount of subsidence at A, b is the amount of subsidence at B, and AB is the horizontal distance between them, then,

$$\text{Slope}_{AB} = \frac{b-a}{AB} . \qquad (2)$$

On average, for the data in the Subsidence Engineers' Handbook, the following relationship is found to be the case:

$$G = 2.75\ S_m/h \qquad (3)$$

where G is the maximum slope. Maximum slope occurs at the inflection points along the subsidence profile.

Subsidence may result in either an increase or decrease in the local ground surface slope, depending upon the original topography. The gradient of any stream channels traversing the affected area will also be changed. Channel slope has been related to channel geometry and behavior by a number of investigators. Leopold and Wolman (18) found a relation between channel slope, bankfull discharge, and channel pattern (figure 7) which indicated that for a given bankfull discharge, channel pattern changes from meandering to braided when a threshhold slope is exceeded. Friedkin (19), Lane (20), and Ackers and Charlton (21) report similar findings.

A change in slope can also result in a change in the stream's ability to erode and transport sediment. Simons, et al. (22) established a proportionality between bed material transport (Qs), slope (S), water discharge (Q), and median fall diameter (D_{50}) where,

$$Q\ S \sim Qs\ \ D_{50} . \qquad (4)$$

This relation is essentially the same as that proposed by Lane (20). It indicates that an increase or decrease or one variable in the equation must be balanced by an increase or decrease in another.

Assuming the water discharge and median fall diameter of a typical stream remain constant, then an increase in slope must be compensated for by an increase in bed material transport so

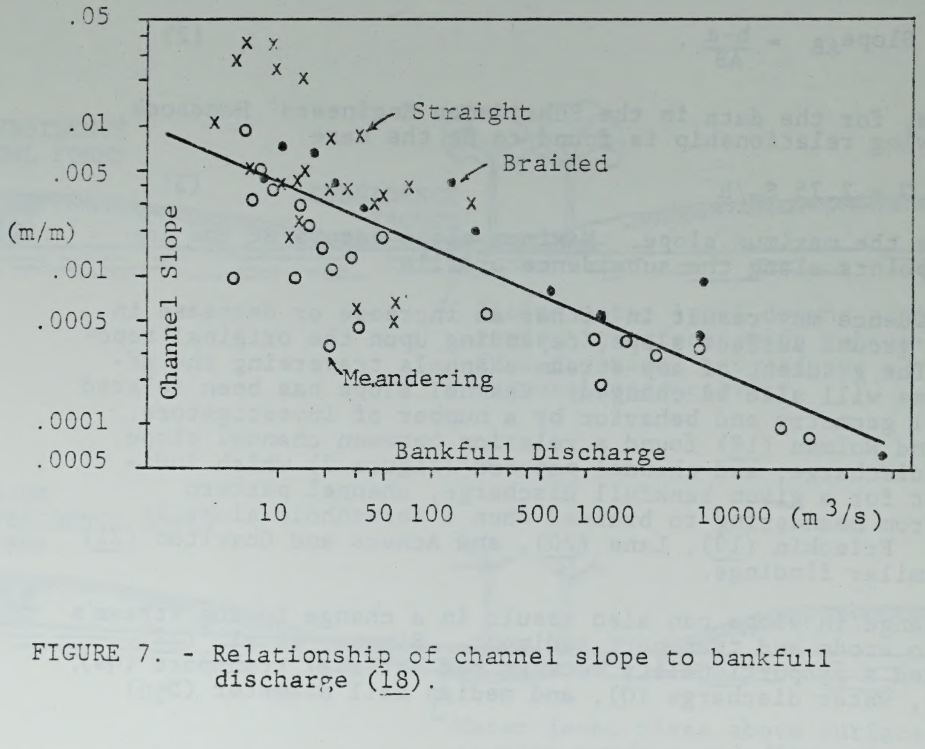


FIGURE 7. - Relationship of channel slope to bankfull discharge (18).

that, $Q S^+ \sim Qs^+ D50$. The increased bed material is produced by erosion of the stream channel bed and banks upstream from the slope change.

Given similar conditions and a decrease in slope, it can be seen that bed material transport must also decrease so that, $Q S^- \sim Qs^- D_{50}$. In this case deposition will occur accompanied by a possible change in channel morphology and increased flooding hazard.

Schumm (23), in a study of ephemeral stream channels in the western United States, found that the processes of erosion were strongly influenced by the nature of the sediments being moved through and deposited in the channel. When sediments contained a large percentage of finer-grained material, silt and clay, erosion took the form of a vertical incision producing a deep, narrow trench. In more sandy material, erosion of the channel banks was dominant, producing a channel widening effect. Depositional processes were also dependent upon the nature of the stream transported material. Generally, fine-grained silts and clays tended to adhere to channel banks causing a narrowing of the channel and forming concave stratification. In channels where sand sized particles were predominant, deposition was essentially horizontal across the channel floor creating horizontal stratification. These sediment dependent modes of stream behavior in part determine the nature of changes in channel morphology over subsided areas and affect the flood susceptibility of the channel during high flows.

Subsidence due to the extraction of ground water in the Santa Clara Valley, California, has given rise to flooding problems associated with changes in stream gradients. Roll (24) describes a flattening of the slope of two major streams, the Guadalupe River and Coyote Creek, and several smaller streams. The resulting loss of sediment transport capacity has in some cases resulted in six-foot deep deposition in a channel that was originally 8 to 10 feet deep, thereby impeding the flow of water and increasing the threat of flooding.

Subsidence accruing primarily from water and oil extraction has occured in the San Joaquin Valley, California. There, large areas of the valley floor have subsided and the increased stream gradients allow an increase in flow velocity. "The steeper gradients in the streams generally allow more water to be carried, decreasing the potential for flooding along stream beds leading into the valley. However, many of the stream beds enter the floor of the valley in curvilinear courses with many oxbow bends. Where the course bends back towards the mountains, the gradient decreases due to subsidence. This increases the probability that a rush of water from the mountains may have to leave the banks of the streambed, causing a flood" (14).

Surface Fissures

The ability of the subsidence process to open cracks or fissures at the ground surface is well documented. Fissures are significant for surface water hydrology because they represent pathways through which surface water can be diverted underground.

The subsidence in the Las Vegas Valley of Nevada is primarily a response to the withdrawal of large quantities of groundwater (14). "Ground surface ruptures in the form of cracks and fissures have occured in Las Vegas Valley as a result of tensile stresses associated with differential subsidence. These fissures begin as small cracks less than an inch wide, but may be widened to several feet across as a result of erosion."

Portions of the central part of Arizona have also experienced subsidence owing to groundwater extraction (14). The most common subsidence feature is fissuring which originates as tension cracks near the edge of a subsidence bowl. Schumann and Poland (25) describe these fissure zones: "The fissures roughly parallel the surface contours and transect natural drainage patterns. Upon application of irrigation water or following high-intensity rainstorms, the fissures intercept overland flow and act as drains. The water moves downward into the fissures causing them to increase rapidly in width - as much as several feet in places. The fissures widen partly by slumping but mainly by erosion of the sides. Gullying often occurs on the upstream side of the fissure. The fissures tend to connect and to form fissure systems that are as much as 8 miles long".

Nishida and Goto (26) report on a number of small irrigation ponds in the Kyushu coal fields of Japan which have been damaged by subsidence over mined coal seams. Of those described, twelve have experienced partial or complete loss of water through leakage into open surface fissures which appeared in areas of tensile strain. Among their conclusions were that a thick clay layer in the pond bottom prevents leakage and if there is a pre-existing fault near the surface, there is a greater possibility of a crack appearing than there would be in an undisturbed area. They also found that if the magnitude of calculated tensile strain at the bottom of a pond is larger than 2 millimeters per meter (mm/m) a year, cracks may appear and cause leakage or complete drainage from the pond.

Dunrud (5) describes the hydrologic significance of fissures opened over the Oliver No. 2 coal mine located south of the North

Fork Gunnison River in western Colorado. Field evidence indicates that subsidence fractures formed in the strata over the mine and migrated to the surface where they intercepted water flowing from springs above the mined-out area. The presence of large, dry beaver ponds, with dams as much as 6 feet high indicate that a perennial water supply was once available from nearby springs which have been dry or flowed intermittently since mining operations took place.

Orchard (12) has compiled and investigated a number of documented examples of fissures opened in a single well-observed coal field (Nottinghamshire) in Great Britain. These are described in table 2. Orchard points out that there are examples of coal fields where pre-existing fractures or joints have been opened up by ground movement and have served to drain away surface storm water. One such example is the large fissures found at the West Cannock Colliery in Great Britain. These were up to 4 feet wide and disproportionate to the associated tensile strains, indicating they had been further widened by the erosive effects of surface water. Orchard notes having seen fissures in strata of widely differing strength, including marl, pebble beds, and even sand. He concludes that relative rock strength may therefore be of limited importance and little correlation has been found between rock strength and liability to fissuring. He further notes that fractures are often found to be of limited depth (say 50 feet) perhaps due to mining-induced compressive stresses located deeper in the overburden. In addition, he also found that the shallow depth of some fissures may limit their capacity to siphon surface water.

As a result of observations similar to those outlined above, the National Coal Board of Britain has adopted minimum standards for preventing the inrush of sea water through fissures associated with coal mining under the sea. Orchard (12) states that consideration was first given to a 5 mm/m strain limit to avoid fissuring. Later a change was made in view of the fact that the British Coal Measures contain a certain proportion of impermeable strata which would prevent the migration of seawater below the limits of the surface fractures. The new standards were accordingly set at 10 mm/m with a minimum overburden thickness of 350 feet for longwall extraction, of which at least 200 feet must be carboniferous (Coal Measure) strata.

Strain Prediction

Since fissures occur as a result of strain induced by subsidence into a mined void, it is important to be able to predict the strains which will be associated with a particular mine site.

Table 2. - Examples of surface fissures in a coal field in Great Britain (12)

Seam Depth (ft)	Other Seams Worked (+ Above) (- Below)	Tensional Strain in mm/m. Estimated or Measured	Surface Geology	Location of Fissure or Fracture	Nature of Fissure
2040	None	4.0 measured	Sandstone 450 ft thick	Parallel to rib-side 540 ft outside	1 in. wide vertical fracture
375	None	5.5 estimated	Unconsolidated deposits over coal measures	Parallel to and over the face	3/8 in. wide fractures
1059	-217 ft	2.2 measured	Conglomerate	Over face following subsidence contour	1 in. crack in ground surface
726	+81 ft +51 ft	4.8 measured	Sandstone 57 ft thick	Parallel to and over coincident ribside of three seams	2 in. fracture in surface
450	+24 ft -48 ft -100 ft	4.9 estimated	Coal measures	Parallel to approximate coincident ribs of four seams 150 ft outside rib	2 in. to 12 in. wide: Fractures 15 ft deep minimum
360	-300 ft	10.8 estimated	Coal measures	Associated with 150 ft barrier of unworked coal in four seams. Fissures at 30 degrees to and crossing barriers	6 in. wide fissures up to 750 ft in length

Table 2. - Examples of surface fissures in a coal field in Great Britain (12) - continued

Seam Depth (ft)	Other Seams Worked (+ Above) (- Below)	Tensional Strain in mm/m. Estimated or Measured	Surface Geology	Location of Fissure or Fracture	Nature of Fissure
510	+100 ft	4.1 estimated	Coal measures	Over edge of unworked coal in seam at +100 ft. Parallel to and 150 ft outside ribside	720 ft long, 18 in. wide
1080	-648 ft	2.0 estimated	Conglomerate	Parallel to and 30 ft outside rib	wide fissure
1590	None	2.0	Limestone	Generally parallel to face. Line 300 ft in front of face	300 ft long, up to 1 in. wide

The movements of points on the surface above a mined panel not only have a vertical component (subsidence) but also a horizontal component called displacement. Horizontal displacements increase from zero at the outer limits of the trough profile to a maximum at the point of maximum slope, and decrease to zero at the trough center. Horizontal and vertical movement at each point on the surface combine as strains across the width of the trough. Figure 8 illustrates how a strain curve can be drawn to indicate the unit strain (change in length expressed as unit change per unit length) occuring at different points on the surface. Stretching or extension is indicated by the portion of the curve drawn above the horizontal datum (plus sign) and shortening or compression is indicated by the portion of the curve below the datum (minus sign). The transition from tension to compression normally occurs at or near the inflection point where subsidence is equal to half of its maximum value.

The magnitude of strain at any given point across the width of the trough can be viewed as a function of the amount of curvature in the subsidence profile. The sharper the curvature, the larger the strain. Profile curvature is sharpest for thick seams mined at shallow depths. There are two reasons for this: (1) thicker seams increase total subsidence and therefore increase the vertical distance between the points of zero and maximum subsidence, and (2) shallow depths result in narrower trough widths (for a given limit angle and panel width) and therefore decrease the horizontal distance between points of zero and maximum subsidence. Profile curvature must be sharper in order to traverse a larger vertical distance over a smaller horizontal distance. Given these relationships, it is apparent that strain (e) is directly proportional to maximum subsidence (S) and inversely proportional to seam depth (h) so that,

$$e \sim S/h. \qquad (5)$$

Since surface fissures occur in the zone of tensile strain and particularly where maximum tension exists, it is necessary to be able to predict the nature and location of the tensional strains associated with a given mine configuration in order to assess the likelyhood of surface fissures occuring. Figure 9, taken from the Subsidence Engineers' Handbook, is a plot of the width-depth ratio of the panel against the distance (d) from the center of the panel (perpendicular to the panel centerline) in terms of depth (d/h) and gives the amount of strain, e, as a proportion of maximum strain, E (+E for tensile strain) where

$$+e = b(+E) \qquad (6)$$

and b is a proportionality constant. By determining values of +e for each point, d, across the width of the trough, a tensile strain profile may be plotted above the previously plotted subsidence profile. Values for +E can be computed using figure 10

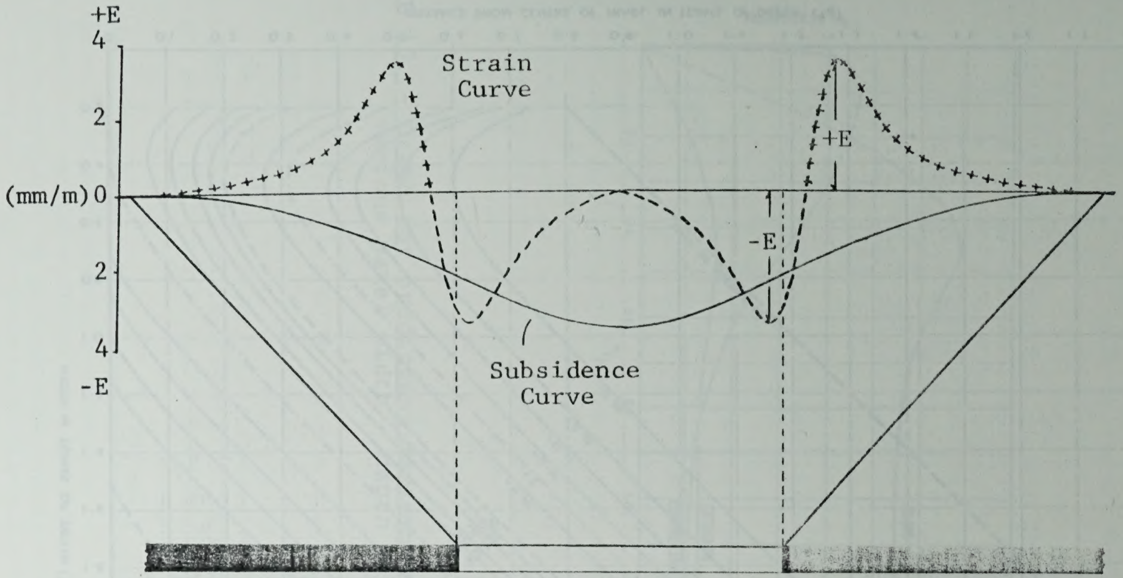


FIGURE 8. - Illustration of a strain curve.

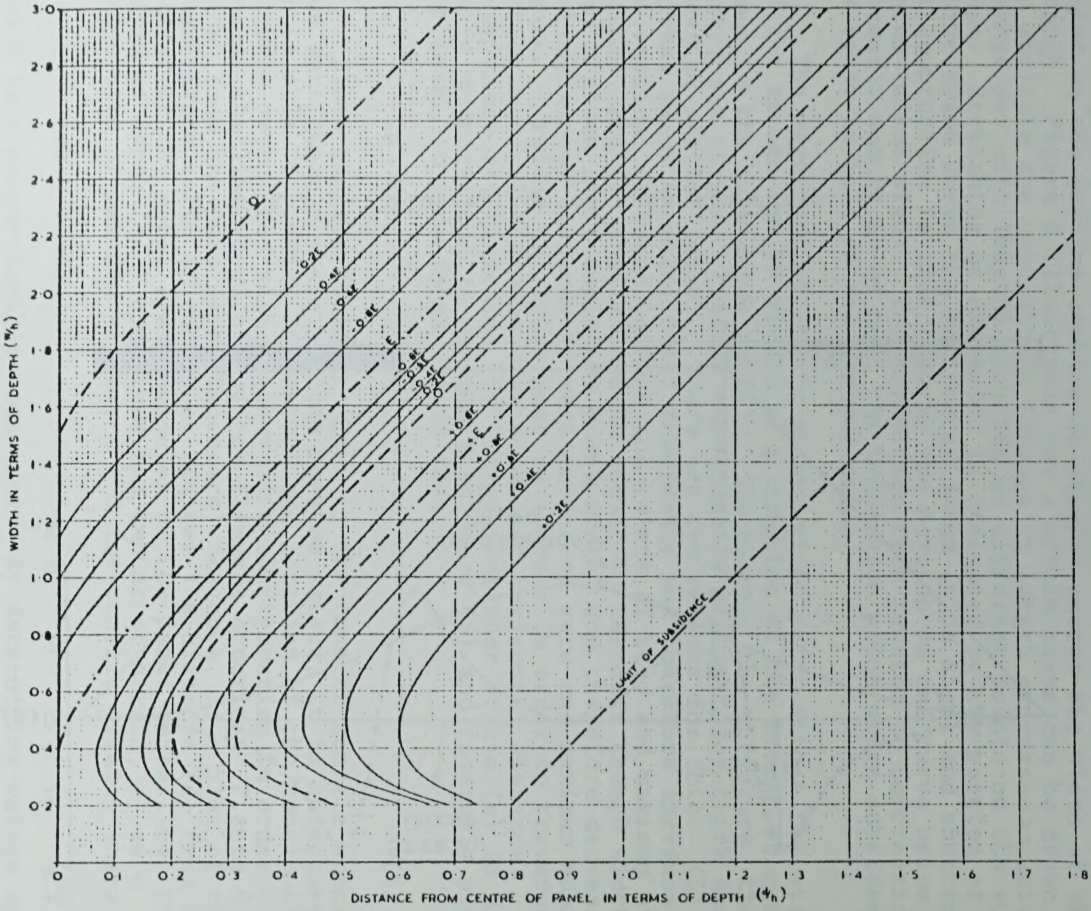


FIGURE 9. - Graph for predicting strain profiles (4).

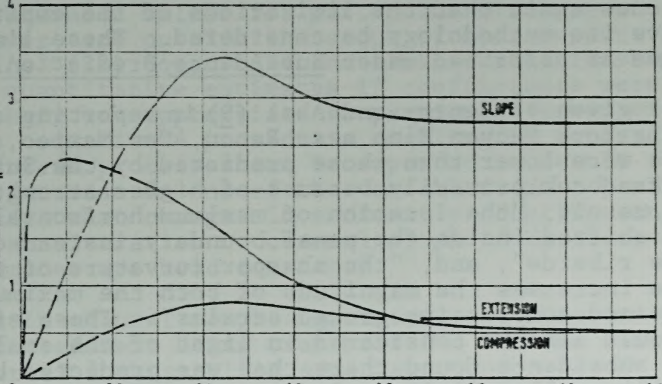


FIGURE 10. - Graph for predicting maximum strain for various panel width - depth ratios (4).

from the Subsidence Engineers' Handbook (4). For known values of w/h, the appropriate multiplier is read off using the curve labeled "extension". The multiplier times S/h (see equation 5) is equal to +E.

Strain has also been found to vary with the slope of the ground surface and the dip of the seam. The Subsidence Engineers' Handbook contains methodologies which allow these effects to be accounted-for.

The use of the Subsidence Engineers' Handbook for strain prediction requires once again that the limitations of the empirical data used to derive its methodology be considered. These limitations are the same as described under Subsidence Prediction.

An example is given by Gentry and Abel (9) in reporting on subsidence over the York Canyon Mine near Raton, New Mexico. Limit angles there were lower than those predicted by the Subsidence Engineers' Handbook primarily because of higher strength overburden. As a result, "the location of maximum horizontal tensile strain is shifted inside the panel boundary instead of occuring above the ribside", and, "the sharper curvature of the subsidence profile increases the magnitude of both the maximum horizontal tensile and compressive ground strains". These effects however, should also be considered in light of the smaller amount of maximum subsidence found there than was predicted by the handbook. While smaller limit angles cause profile curvature to increase for a given amount of subsidence, a decrease in maximum subsidence causes a decrease in curvature and therefore the actual curvature may be closer to that predicted by the handbook than would be expected if only the smaller limit angles were considered.

Summary of Impacts on Surface Water Flow

Quantitative estimates of changes in the ground surface configuration above a mined panel are possible using the methodology contained in the Subsidence Engineers' Handbook. The handbook is used in this study to compute S_m (or S if the panel width is subcritical) and to plot the subsidence profile. The amount of vertical settlement at various points across the width of the panel can then be measured from the profile.

The lateral extent of vertical settlement is shown by the points of interception of the ground surface by the lines defining the limit angles. Equation 3 is used to compute the maximum change in slope when panel width is critical or supercritical. For subcritical panels, S is substituted for S_m. Slope change is considered with reference to the local topography in order to assess whether it results in an overall increase or decrease in surface slope. If changes in slope along different segments of the profile are required, they can be computed using equation 2.

For investigating changes in surface streams, figure 7 is derived from empirical data but is limited by the range of data and therefore cannot be used for quantitative predictions. It can be used in a qualitative manner to indicate the type of possible change in channel pattern which might be expected from a particular slope alteration. Development of similar curves for particular areas of interest would allow quantitative estimates to be made of threshold values for particular discharges. Such curves, however, are outside the scope of this report. Likewise Simons,et al's. (22) equation 4 and similar relationships could be used for quantitative estimates if coefficients were derived which made their use appropriate to particular areas of interest. As it stands, equation 4 provides a qualitative sense of what changes in stream processes can be expected to result from an increase or decrease in one of the variables (most particularly for this study, what changes in sediment production can be expected from an alteration to channel slope if discharge and median fall diameter are held constant).

Changes in channel morphology are also a function of the nature of the sediment being transported. Streams carrying fine-grained material such as silts and clays tend to erode vertically and to narrow when depostion occurs. Channels carrying sand sized material tend to erode their banks horizontally and create wide horizontal stratification when depositional processes are predominent. The types of sediments available for transport will therefore in part determine the alterations to channel morphology associated with subsidence-induced changes in channel slope.

Amounts of surface tensile strain can be computed using the methodology from the Subsidence Engineers' Handbook, as described. Tensile strains are plotted above the subsidence profile so that amounts and corresponding locations can be visualized. The literature indicates that tensional strains above 2 mm/m have the potential to create fissures. Strains in the area of 10 to 11 mm/m or higher almost certainly will result in fissuring. The 5 mm/m limit first proposed by the National Coal Board of Britain is perhaps a good conservative minimum value for assessing at what point significant hydrologic impacts can be expected. Depth of overburden and other local conditions are also important considerations.

Use of the Subsidence Engineers' Handbook is a conservative approach because the data comes from areas of weak strata, thus giving rise to maximum subsidence. Surface water impacts based on the predicted subsidence parameters can therefore be considered to be the worst case in most instances. When appropriate, it is noted whether or not the geologic and topographic characteristics of a particular site might cause the actual subsidence parameters to deviate strongly from those predicted by the handbook.

Several case histories have been cited concerning the nature of surface water hydrology impacts associated with subsidence caused by withdrawing oil and water from underground. Because these case histories pertain to extensive surface areas that have subsided, they have application to the wide subsidence trough or basin formed over a plurality of adjacent longwall panels, but do not apply to the narrow subsidence trough over a single longwall panel. A stream channel crossing a narrow trough may be disrupted by fissuring, settlement, and changes in slope over a short distance, which combined can cause complex interactions that trigger erosion or deposition, but which later may be dampened by the trough filling with water. Such changes may occur progressively along the stream channel as subsequent longwall panels are mined until a wide trough forms and mining ceases. The stream conditions across the wide trough may be similar to those across large subsided areas caused by withdrawing oil or water from underground.

Finally, the effects of subsidence on surface hydrology are to a large extent site specific. There are so many factors which are unique to each particular site that with the range of data presently available it is not possible to use the results of one case study to formulate a quantitative methodology which can then generally be applied to other sites. Each site must be interpreted in the context of its own unique set of environmental parameters. Surface water impact prediction is therefore limited by the range of data available and the scope of this study to qualitative rather than quantitative assessments.

Impacts on Surface Water Quality

Changes in surface water quality associated with subsidence over a mined longwall panel are induced primarily through three processes: (1) alterations to the quality of the groundwater which, later, through seepage, contributes to the base flow of surface streams, (2) changes in stream channel slope which lead to changes in the stream's sediment load and, (3) changes in the configuration of the land surface drained by a stream channel which result in increased or decreased overland sediment production.

Alterations to groundwater quality are discussed under Groundwater Impacts. The relationship of channel slope to sediment load was discussed previously in this section. Change in surface configuration owing to subsidence and its relationship to increased sediment production is generally recognized in the literature but no case history studies were found which focused on this problem.

McKee and Wolf (27) as referenced by Hill (28) list a number of effects which increased sediment load has on the environment. Sediment reduces light penetration and alters water temperature, which in turn affects aquatic flora and fauna. Fish are additionally affected by the smothering of food organisms in sediment, destruction of spawning grounds, and the filling of pools. Deposition of excess sediment increases the hazard of flooding by reducing a channel's carrying capacity.

The tendency for a section of land to produce sediment through erosion is described by the Universal Soil Loss Equation. Utilization of this equation is discussed in a handbook written by Wischmeier and Smith (29) and published by the U.S. Department of Agriculture.

The Universal Soil Loss Equation consists of one dependent and six independent variables:

$$A = RKLSCP, \tag{7}$$

where, A is the soil loss in tons/acre,

R is the rainfall factor,

K is the soil erodibility factor,

L is the length of slope factor,

S is the steepness of slope factor,

C is the cropping and management factor,

and P is the erosion control practice factor.

The formation of a subsidence trough on the land surface affects the slope factors, L and S. Subsidence may increase or decrease the slope length (L) depending upon the pre-existing topography. Slopes may also be created which weren't there before and pre-existing slopes may be partially leveled, changed in direction, or eliminated. Erosion and transportation of sediment are directly proportional to slope length because increased slope length results in increased runoff volume and velocity. Changes in the surface configuration induced by subsidence may therefore alter sediment production, stream sediment load, and consequently surface water quality.

Increases in the steepness of slope (S) result in increases in flow velocity and in the capacity for erosion by water running off the land surface and ultimately into the stream channel. Changes in the steepness of slope owing to mining subsidence are also in part dependent upon pre-existing topography.

The ultimate effects of changes in the slope factors owing to subsidence are of course dependent upon the values for the other factors in the Universal Soil Loss Equation. For instance, the drastically different climates in the eastern and western parts of the United States give large differences in the rainfall factor, R, and the cropping factor, C (in terms of vegetation density), from one region to the other. The relatively small changes in slope associated with subsidence may have much less effect in the Appalachians due to a high vegetation density than they would in the west where the soil has much less protective vegetation cover. Equation 7 can be used to make quantitative predictions on soil loss and therefore stream sediment load when all of the independent variables are known. Since a determination of these variables is not possible within the scope of this study, equation 7 is limited to qualitative estimates of changes in sediment load owing to subsidence-induced changes in one or both of the slope factors.

Summary of Impacts on Surface Water Quality

Surface water quality can be altered by subsidence through changes in the quality of groundwater base flow and through increased or decreased sediment production from overland and stream channel flow. A search of the literature provided no systematic studies of changes to surface water accruing from subsidence over totally extracted thick coal seams. Therefore, no quantitative methodology for prediction of surface water quality changes was formulated.

The Universal Soil Loss Equation can be used to qualitatively assess the direction of change in stream sediment load to be expected from changes in its slope factors owing to subsidence. Quantitative estimates however, will require an acquisition of data pertinent to western coal seams which is beyond the scope of this study.

Groundwater Impacts

The strains imposed by the movement of overlying strata into the void created by mining a longwall panel can affect the hydrogeologic environment through the inducement of caving, fracturing and fissuring. These breaks and fractures create a secondary or fracture permeability. Rocks which had a low primary permeability (the permeability of the original interstices created when the rock was formed) and therefore served as barriers to groundwater flow may, as a result of fracturing, become conduits for groundwater migration. In this way, water-bearing formations which were previously segregated from one another may be hydraulically connected and the groundwater flow regime significantly altered.

Orchard (12) cites the example of an inrush of water at 14,500 gal/min at the Coppice Pit in Great Britain. A marl bed in the roof of the mine fractured due to undermining of a coal seam and overlying water-bearing sandstones and conglomerates which had been separated from the coal seam by the impervious marl were allowed to drain into the mine.

Alterations to the properties of the groundwater media can, in turn, induce changes in the quality of the groundwater itself. Water is allowed to come in contact and react with minerals exposed by the mining process and the resulting strata disruption. Waters of different aquifers which were formerly isolated by impermeable strata are allowed to mix and alter in quality towards some average value.

Impacts on Groundwater Flow

The initial step in analyzing the impacts of subsidence on hydrogeology requires a number of approximations to be made concerning the nature of fracturing or caving above a mined panel. The first involves an estimate of the height above the mine roof that the fracturing will occur. This knowledge, combined with a knowledge of the water-bearing characteristics of the overburden stratigraphy enables a determination to be made as to whether an overlying aquifer will be intercepted by the fractured zone.

Second, the nature (that is, intensity, orientation, etc.) of the caving or fracturing at progressive heights above the panel needs to be understood in order to make a qualitative assessment of the anticipated changes in hydrogeology.

Finally, a quantitative estimate of anticipated increases in permeability is desired in order to be better able to predict the magnitude of the groundwater impacts.

Height and Nature of Roof Caving and Fracturing

Disruption and fracturing of the overburden owing to caving into a mined panel void occurs primarily in the near roof above the panel where flexure of the strata is greatest. Thomas (30) states that, "The caving height depends on the ease of fragmentation of the roof beds, but can be about three to eight times the seam height extracted." Wilson (31) points out that the broken roof material should occupy about 1.5 times the volume of the unbroken roof material (that is, a swell factor or ratio of in situ roof material density to fragmented roof material density, g, of 1.5). Therefore, if the roof caves efficiently, by the time caving reaches 3 or 4 times the height of the extracted seam, there will be enough broken material to fill the mined void and the caving will stop. Above this caved zone he describes a zone where the roof will be jointed and cracked but individual pieces of material will maintain their spacial orientation with the material around them. Ropski and Lama (32) state that the height of primary caving (where roof material is fractured into small pieces and reoriented) is usually taken to be about 5 times the thickness of the extracted seam, and a zone which additionally includes that material which is highly fractured but maintains some degree of orientation is usually taken to be 8 to 10 times the extracted seam thickness. Kenney (33) describes the height of the caving zone as being to a large extent dependent on the ratio of the in situ roof material density to its bulk density when fragmented. He states that, "The active caving is limited in vertical extent by virtue of the decrease in density of the roof material on fragmentation. Broken rock occupies a volume about 1½ times that of solid rock so that, if W is the height of extraction of the face, a thickness of roof of 2W will provide sufficient material to fill the space." Kenney also suggests that the height of caving can exceed the limit imposed by the caved material density if the angle of the debris pile accumulating behind the mined face becomes equal to the angle of repose of the fragmented material. Material can then roll from the top of the pile and be effectively flushed into the as yet uncaved area just behind the roof supports. Further caving is then required to fill the void. Wardell (11) notes that, "The height of actual collapse is limited by the height of the void and by the change in volume of the collapsed material. The height of collapse is rarely more than ten times the height of the void or cavity."

The two most comprehensive case histories dealing with the height of caving found in the foreign literature review came from the Velenje lignite mine in Yugoslavia and from the Lenin Colliery in the Upper Silesian coalfield in Poland.

Information on various investigations conducted at the Velenje Mine is reported by Sovinc (17). At the Velenje Mine lignite seams of great thickness (50 to 80 meters thick) are being mined underground at a depth of 140 to 450 meters. The seams are mined by the longwall caving method in benches 7.5 to 11 meters high. Several faces are over 50 meters long. Since the groundwater level is near the surface, the surface depression formed by subsidence over the mined panel accumulates water. One of the largest lakes is over 40 meters deep now, and with planned future works will become still deeper.

The Velenje region is divided into the eastern and western fields by a safety pillar. The overburden of the western field is between 300 and 450 meters thick. Sandy clays and clays with sand or gravel intercalations prevail in it. The proportion of pure clay and sand is different in various places. The impermeable strata to permeable strata ratio is between 0.2 and 2.3. In the hanging wall immediately over the lignite seam there is a semihard to hard clay and marly clay from 10 to 300 meters thick. Artesian water has been registered in the sand and gravel strata. The marly clay strata display low permeability.

The investigations reported in Sovinc's paper were made to find out whether there was a danger of lake water breaking into the mine and to determine the thickness of isolating clay layers over the faces of the western field necessary to protect them not only against direct inrushes of water from the permeable strata above the lignite through the caved and fractured overburden, but also against flooding of the gob (caved material) through thin fissures at the surface. The problems arising in connection with working under such conditions are primarily associated with determination of the height of caving.

Hydrological investigations conducted at the Velenje Mine in 1942 indicated that the clay strata above the coal seam were practically impermeable. A report prepared by a consultant stated that there was no danger of surface water entering the mine. Caving of the overburden would occur only up to a height determined by the equation:

$$C = \frac{m}{g-1}. \tag{8}$$

From this formula, with a swell factor of $g = 1.3$ and a working lift of $m = 8$ meters, a caving height, C, of 27 meters or about 3.4m, was calculated. To allow for a sufficient safety margin, it was further stipulated by the consultant that: (1) the thickness of the immediate clay strata in the overburden must be 50 meters and, (2) the mining limits of two benches must not overlap in the ground plan, and they must be well apart for a triple working lift.

Later, in 1958, the safety of mining under water accumulations at the surface was investigated by other consultants. They recommended a number of investigations before any mining operations could be initiated: (1) rock testing to assess the shear strength and compressibility of the clay layer, (2) stress and deformation measurements for analyzing the caving process and consolidation, and (3) measurements of the swell factor of the caved clay.

In 1964, principally on the basis of practical experience in the mine, the minimum thickness of the isolating clay layer between the face and a water-bearing seam for which dewatering was not necessary was fixed at 45 meters or 6m for a working lift, m, of 7.5 meters.

Subsequent to the establishment of these provisional criteria, especially in 1968 and 1969, extensive investigations were carried out in the mine. These investigations included the measurement of roof arch heights as reported by Hrastnik (34). Figure 11 shows how the broken zone in the overburden is confined within a pressure arch formed in response to the stresses imposed by mining. Measurement of the height of the roof or pressure arch is of interest because it provides an estimate of the height of the heavily disturbed (caved) zone and permits calculated values to be checked.

The roof arch height was measured by recording the penetration rate of a rotary drill bit. Drilling at constant pressure was performed from the roadway below the horizon being worked. It was found that the variation of drilling rate between the unbroken and the caved hanging wall was distinct enough to give a reliable criterion for determination of the height of the caved zone. Above this zone, there was still a zone of cracked clay whose resistance was found to vary over a rather wide range.

In order to relate the roof arch or caved height to measurable parameters for prediction purposes, a number of other tests were made. In the unbroken hanging wall before the face and in the broken hanging wall at several distances behind the face, pressures were measured in situ. Consolidation of the broken hanging wall and coal was investigated in the laboratory in a large confined compression test under the same pressures as were measured in situ. In this way, an analytical expression was obtained for the roof arch height (height of caving) at any time after the passage of the mining front:

$$C = \frac{m_{ef} + m_{pi}\ (1 - g_p)}{g_g - 1} \qquad (9)$$

where C = roof arch height,

m_{ef} = thickness of coal extracted,

m_{pi} = thickness of coal left in roof,

g_p = swell factor of coal,

and g_g = swell factor of clay.

The swell factors g_p and g_g are time dependent and were derived from laboratory tests which yielded four equations. For mining under undisturbed overburden,

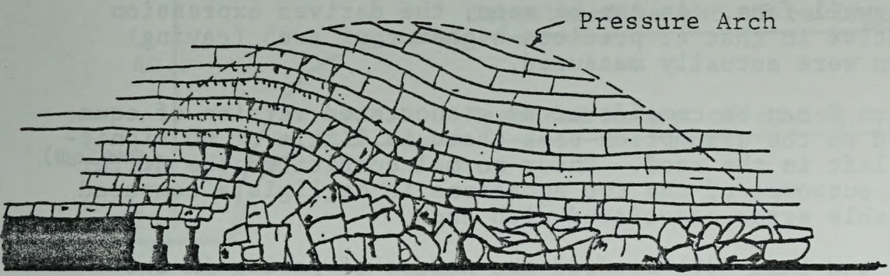


FIGURE 11. - Formation of a broken zone in the overburden.

$$g_p = 1 + 0.488e^{-0.162t} + 0.277e^{-0.0163t} \qquad (10)$$

and $$g_g = 1.408 + 1.255/t. \qquad (11)$$

For mining where the overburden has been disturbed by previous mining,

$$g_p = 1 + 0.622\ e^{-0.253t} + 0.153e^{-0.008t}, \qquad (12)$$

and $$g_g = 1.390 + 1.05/t. \qquad (13)$$

The time factor, t, is measured in days.

In figure 12, measured and calculated roof arch height values at the Velenje Mine are plotted versus distance from the advancing longwall face. As can be seen, the derived expression is conservative in that it predicts higher roof arch (caving) heights than were actually measured.

Equation 8 can be considered as a shortened version of equation 9 based on the assumption that there is little or no significant coal left in the roof. Under normal conditions the difference in the outcomes of the two equations is negligible compared to the probable error associated with each.

Ropski and Lama (32) studied the nature of caving in the Lenin Colliery in Poland. The purpose of their investigation was to determine the displacement of the roof rocks over a longwall panel in order to assess the future mineability of coal seams located at a distance above the panel. They point out that, "The formation of the caving zone is dependent upon the nature of the rocks lying above the seam with respect to their capability of caving, the system of support of the face, the method of extraction,and the cycle of operations on the face. The rocks which cave well and at regular intervals immediately after the withdrawl of the support on advance of the face give rise to better support conditions to the top-lying beds which then slowly bend over. In such cases the region of caving and large-scale fracturing (regions of primary and secondary caving) is smaller compared to the conditions where massive beds lie which cave at large intervals in big blocks giving rise to a small increase in the volume of the caved rock."

Measurements were made of the caving above a mined seam of thickness 1.0 to 1.1 meters dipping at an angle of about 6 degrees and lying at a depth of about 220 meters. The seam has a roof consisting of shales, sandy shales, and fine-grained sandstone. Measurement points were established in boreholes and openings in the roof, floor and sides of roadway excavations located above the mined panel.

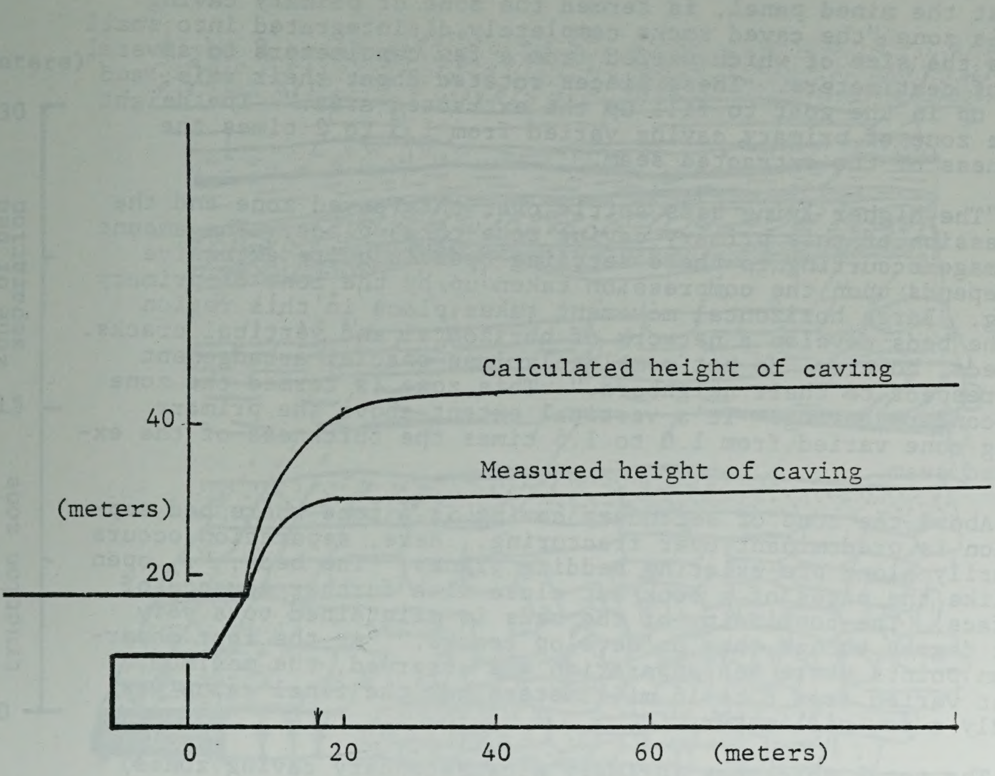


FIGURE 12. - Measured and calculated height of caving during mining a first bench at the Velenje Mine (16).

The caved roof is described by dividing it into three zones based upon the extent of fracturing. The lowermost zone, or that nearest the mined panel, is termed the zone of primary caving. In this zone "the caved rocks completely disintegrated into small blocks the size of which varied from a few centimeters to several tens of centimeters. These pieces rotated about their axis, and piled up in the goaf to fill up the extracted area." The height of the zone of primary caving varied from 1.5 to 2 times the thickness of the extracted seam.

"The higher-lying beds settle over this caved zone and the compression of this primary caving zone takes place. The amount of damage occurring to these settling beds is quite extensive and depends upon the compression taken up by the zone of primary caving. Large horizontal movement takes place in this region and the beds develop a network of horizontal and vertical cracks. The beds, however, do not completely lose spacial arrangement with respect to their neighbors." This zone is termed the zone of secondary caving. It's vertical extent above the primary caving zone varied from 1.0 to 1.5 times the thickness of the extracted seam.

Above the zone of secondary caving is a zone where bed seperation is predominant over fracturing. Here, separation occurs primarily along pre-existing bedding planes. The beds, "...open out like the pages of a book but close with further advance of the face. The continuity of the beds is maintained to a very great degree though they do develop cracks." At the four observation points where bed separation was observed, the maximum amount varied from 8 to 15 millimeters but the final value was, "hardly a few millimeters".

The total thickness (primary plus secondary caving zones) of the roof beds heavily damaged by mining the longwall panel was 3 to 3.5 times the thickness of the extracted seam. It should be noted that the overburden rocks for this mine caved easily and therefore the height of caving was smaller than would have been the case for strong massive roof rocks.

Kenney states that "A source of variation in the boundaries of the supported roof is the type of roof material and its associated density increase on fragmentation. Massive sandstone roofs, for example, tend to cave in extremely large regular blocks." In such cases the swell factor may be very near unity, resulting in large amounts of caving.

Nakajima (35) studied the nature of caving over a longwall mine in Japan. Figure 13 depicts his findings. While Nakajima does not divide the caved roof into three zones as did Ropski and Lama, it is evident from figure 13 that the caving process was similar in the two studies. Nakajima's crack and destruction

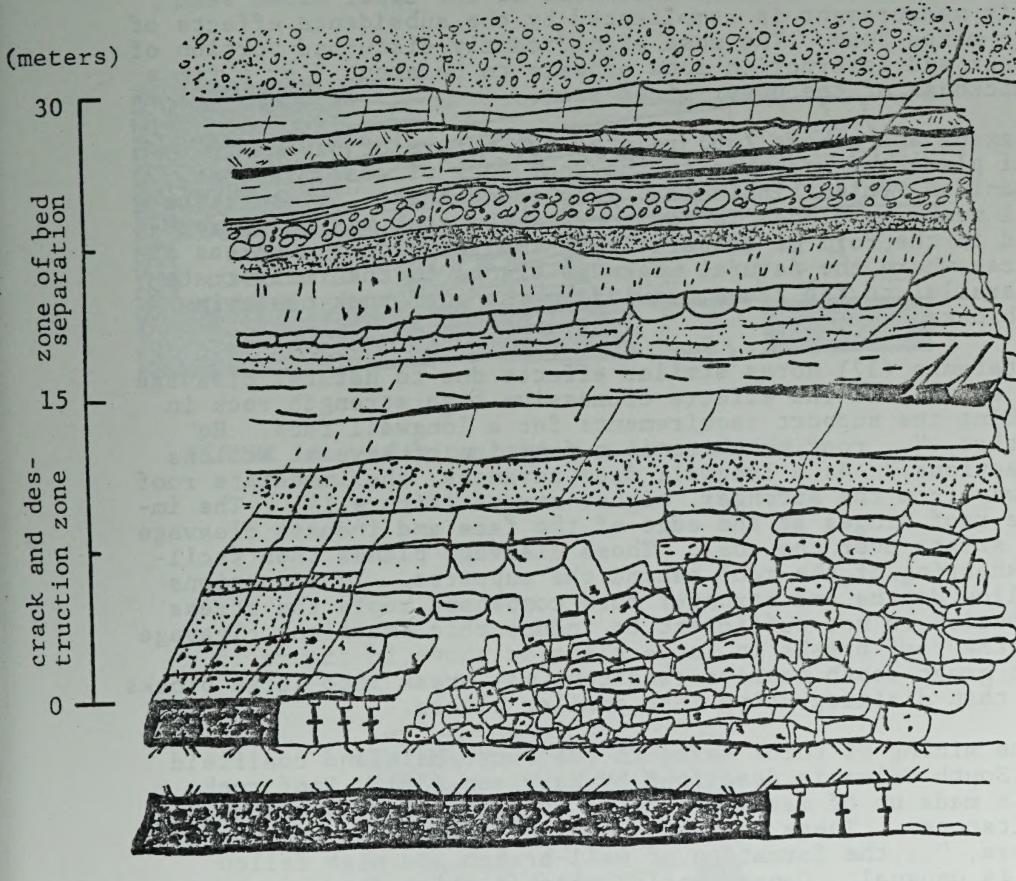


FIGURE 13. - Nature of caving over a longwall mine.

zone corresponds to Ropski and Lama's zones of primary and secondary caving. Both studies describe a higher zone of bed separation with few vertical fractures. The total disturbed height is about 12 to 13 times the thickness of the upper mined seam but this measurement is complicated by the subsidence effects of a lower mined seam. The most significantly disturbed portion of the crack and destruction zone appears to be about 3 or 4 times the thickness of the upper mined seam.

Saxena and others (36) related the nature of caving to natural planes of weakness in the roof rock of coal mines at the Moonidah Project in India. They found that, "...where the natural weakness planes in the roof in the goaf was quite regular and in the form of comparatively smaller blocks, whereas at the faces where the natural weakness planes in the roof strata were parallel to the faces, caving in the goaf took place in large blocks."

Stefanko (37) notes similar effects due to natural cleavage planes as well as the effects of massive high strength rock in describing the support requirements for a longwall face. He notes that, "...roof behavior is a function of several actions and reactions." As a longwall face advances, the immediate roof sags away from the stronger, higher strata (figure 14). The immediate roof hinges at the edge of the face and induces cleavage in the strata over the coal. These cleavage planes then facilitate shearing of the roof behind the supports. In situations of shallow depths and stronger more competent roofs the stress distribution is not sufficient to induce this incipient cleavage and so the roof breaks in large slabs as shown in figure 15. Even at great depth massive sandstone may break into large blocks rather than disintegrating into smaller pieces.

The mining of thick seams in the South Maitland coalfield in New South Wales is described by Harrison (38). Roof rock there is made up of massive beds of conglomerates, sandstones, and siltstones. These strata have high breaking strength and therefore, "...the formation of well-broken and high fallen goaves is unusual. Consequently, where a thick seam has been extracted large voids remain, no closure and compaction takes place.."

Dunrud (5) summarizes the research of a number of foreign investigations. They find in general, that the amount of fracturing in the overburden is somewhat dependent upon the rate of mining: "...slower or variable mining speed increased overburden breakage".

Nakajima (35) looked at the effects of reconsolidation of the caved or broken zone over time. In studying longwall mines in Japan he found that just after mining at Kushiro Colliery the ratio of vacant space to vertical height in the caved

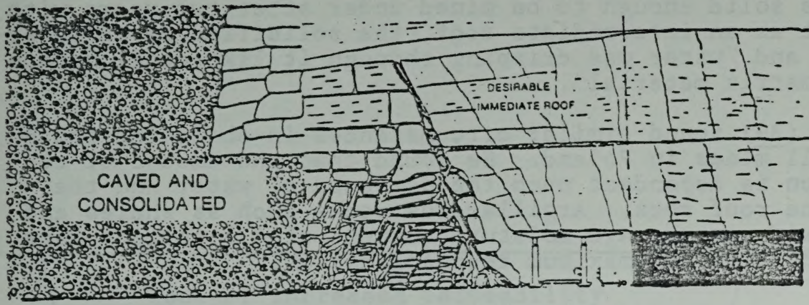


FIGURE 14. - Caving behind a longwall face.

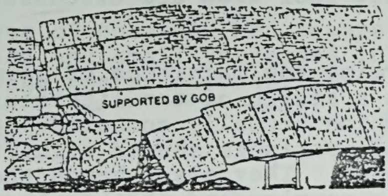


FIGURE 15. - Caving with shallow depth and competent roofs.

roof was about 30%. Data gathered from bore holes in the goaf 2 years after the mining indicated that this ratio had dropped to an average of 6.2%, indicating that much reconsolidation had taken place and that permeability as represented by the vacant spaces in the caved material was greatly reduced over the 2-year period. Nakajima points out that the reconsolidation process requires the presence of water to be most efficient, and that though the roof was solid enough to be mined under after two years with no coal left as an intermediate roof, the solidified caved material was wet and "water was dripping through it like conglomerate with small matrix material".

Sikora (39) found similar circumstances in observing thick seam longwall mines in Poland. He found that the amount of reconsolidation is dependent upon the presence of water and the nature of the roof rock. Argillaceous rocks such as shales and siltstones with an average moisture content of 4.5 percent were considered optimum for maximum reconsolidation.

Permeability Changes

The potential for changes in the permeability of the groundwater medium due to the subsidence effects of underground mining is well recognized. In a study of mine water control in the anthracite region of Pennsylvania, Dierks and others (40) discuss the origin of mine water seepage. They state that, "The greatest seepage must be attributed to the permeability of strata broken by subsidence after mining had ceased." Figure 16 illustrates the general situation with regard to permeability changes over mined-out seams. Permeability changes within the zone of heavy fracturing in the immediate roof area are discussed in this section.

Measurement to determine the magnitude of permeability changes is difficult. In a search of the literature only three case studies were found which actually compared premining and post-mining values. The comparisons showed significant increases in permeability in all cases. They also showed that the processes involved are highly complex and that further study is needed in order to identify all of the significant variables and their relationships to the final permeability value.

Williamson (41) studied the feasibility of mining under reservoir waters near Sydney, Australia. The problem involved determining whether or not large losses of water would occur through the subsidence-disrupted strata. The overburden was generally characterized by large thickness of sandstone interbedded with thin claystone and shale layers. The shale and claystone layers were impermeable and served as barriers to vertical flow between sandstone units.

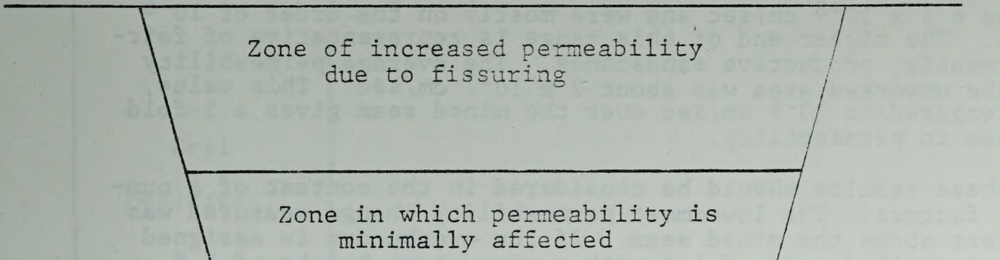

Zone of increased permeability due to fissuring
Zone in which permeability is minimally affected
Zone of possible bed separation and small increases in horizontal permeability
Extracted seam height, m
Zone of caving, heavy fracturing, and increased permeability

FIGURE 16. - Permeability changes over mined-out seams.

Falling head permeability tests were done in a borehole over an unworked area where a panel of about one-third overburden thickness had been extracted from the Bulli seam. The permeability measurements did not permit a segregation of changes in the vertical direction from changes in the horizontal direction. The borehole over the unworked area extended to the base of the Bulli seam and permeability measurements were taken at 6-to 9-meter intervals upward from the seam for most of the length of the hole. Permeabilities were all low, ranging from 4 x 10^{-7} cm/sec down to 5.5 x 10^{-9} cm/sec. These values are typical of relatively impermeable strata such as shale and well cemented fine-grained sandstone. Over the worked area, permeabilities were taken in a borehole upward from 73 meters above the Bulli seam. The cores from over the worked panel had more pronounced fracturing and the measured permeabilities were consistently higher than over the unworked area. They ranged from 4 x 10^{-4} down to 6.4 x 10^{-8} cm/sec and were mostly on the order of 10^{-6} cm/sec. The higher end of this range is representative of fairly permeable, productive sandstones. The average permeability over the unworked area was about 2 x 10^{-7} cm/sec. This value, when compared to 10^{-6} cm/sec over the mined seam gives a 5-fold increase in permeability.

These results should be considered in the context of a number of factors. The lowermost permeability change measured was 63 meters above the mined seam. If the overburden is assigned a normal swell factor of 1.3 with a mined seam height of 1.8 meters, equation 8 gives a caving height of 6 meters. The observed permeability changes therefore, occured well above the height of caving and even above the expected height of significant bed separation (13m or about 23 meters). Permeability increases would, in all likelihood, be a much higher order of magnitude if measured in closer proximity to the mined seam.

While Williamson's study does not measure permeability changes in the caved zone or permit the formulation of a predictive equation, it does indicate that the strata disruptions which take place over a mined panel result in permeability increases of sufficient magnitude to significantly alter the local groundwater flow regime.

Neate and Whittaker (42) studied changes in in situ permeability of the strata over a longwall panel being mined under the North Sea. Lynemouth Mine is situated on the North Sea coast. As is shown in figure 17, a number of coal seams are present in the geologic section. The Main Seam has been worked by the room and pillar system. It lies about 90 meters below the sea bed. The Brass Thill Seam is about 160 meters below the sea bed and was being longwall mined from a panel 1.5 meters thick with a face length of 195 meters and a planned advance of 650 meters. Two boreholes were drilled throughout the strata

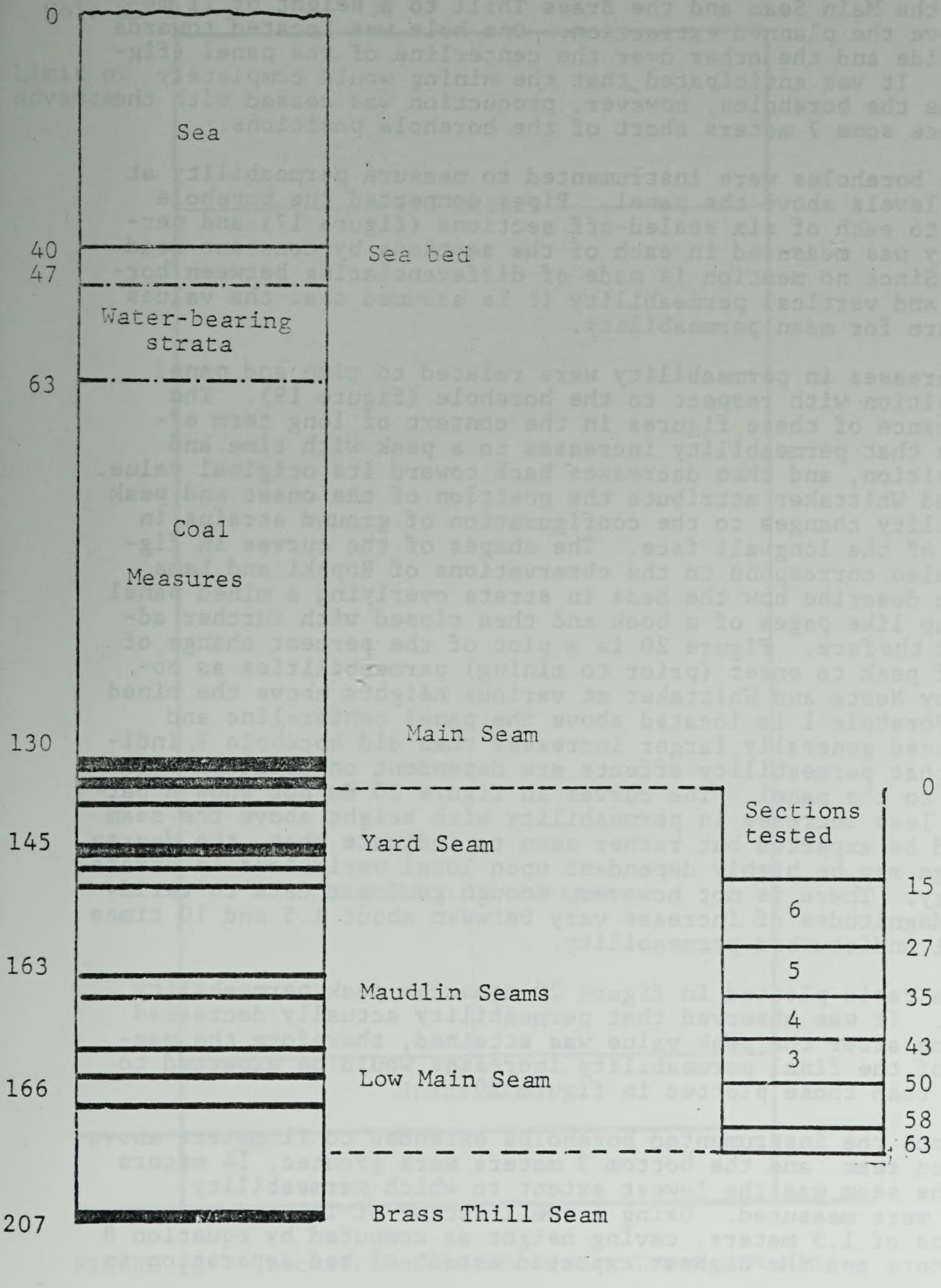


FIGURE 17. - Geology and test section positions at Lynemouth Mine.

between the Main Seam and the Brass Thill to a height of 11 meters above the planned extraction. One hole was located towards one ribside and the other over the centerline of the panel (figure 18). It was anticipated that the mining would completely undermine the boreholes, however, production was ceased with the panel face some 7 meters short of the borehole positions.

The boreholes were instrumented to measure permeability at various levels above the panel. Pipes connected the borehole opening to each of six sealed-off sections (figure 17) and permeability was measured in each of the sections by constant-head tests. Since no mention is made of differentiating between horizontal and vertical permeability it is assumed that the values quoted are for mean permeability.

Increases in permeability were related to time and panel face position with respect to the borehole (figure 19). The significance of these figures in the context of long term effects is that permeability increases to a peak with time and face position, and then decreases back toward its original value. Neate and Whittaker attribute the position of the onset and peak permeability changes to the configuration of ground strains in advance of the longwall face. The shapes of the curves in figure 19 also correspond to the observations of Ropski and Lama (32) who describe how the beds in strata overlying a mined panel opened up like pages of a book and then closed with further advance of the face. Figure 20 is a plot of the percent change of ratio of peak to onset (prior to mining) permeabilities as observed by Neate and Whittaker at various heights above the mined seam. Borehole 1 is located above the panel center-line and experienced generally larger increases than did borehole 2, indicating that permeability effects are dependent on location with respect to the panel. The curves in figure 20 do not show a pattern of less increase in permeability with height above the seam as would be expected but rather seem to indicate that the degree of change may be highly dependent upon local variations in strata lithology. There is not however, enough geologic data to verify this. Magnitudes of increase vary between about 1.5 and 10 times original undisturbed permeability.

The ratio plotted in figure 20 measures peak permeability changes. It was observed that permeability actually decreased over time after the peak value was attained, therefore the magnitude of the final permeability increases would be expected to be less than those plotted in figure 20.

Since the instrumented boreholes extended to 11 meters above the mined seam and the bottom 3 meters were grouted, 14 meters above the seam was the lowest extent to which permeability changes were measured. Using a swell factor of 1.3 and a seam thickness of 1.5 meters, caving height as computed by equation 8 is 5 meters and the highest expected extent of bed separation is

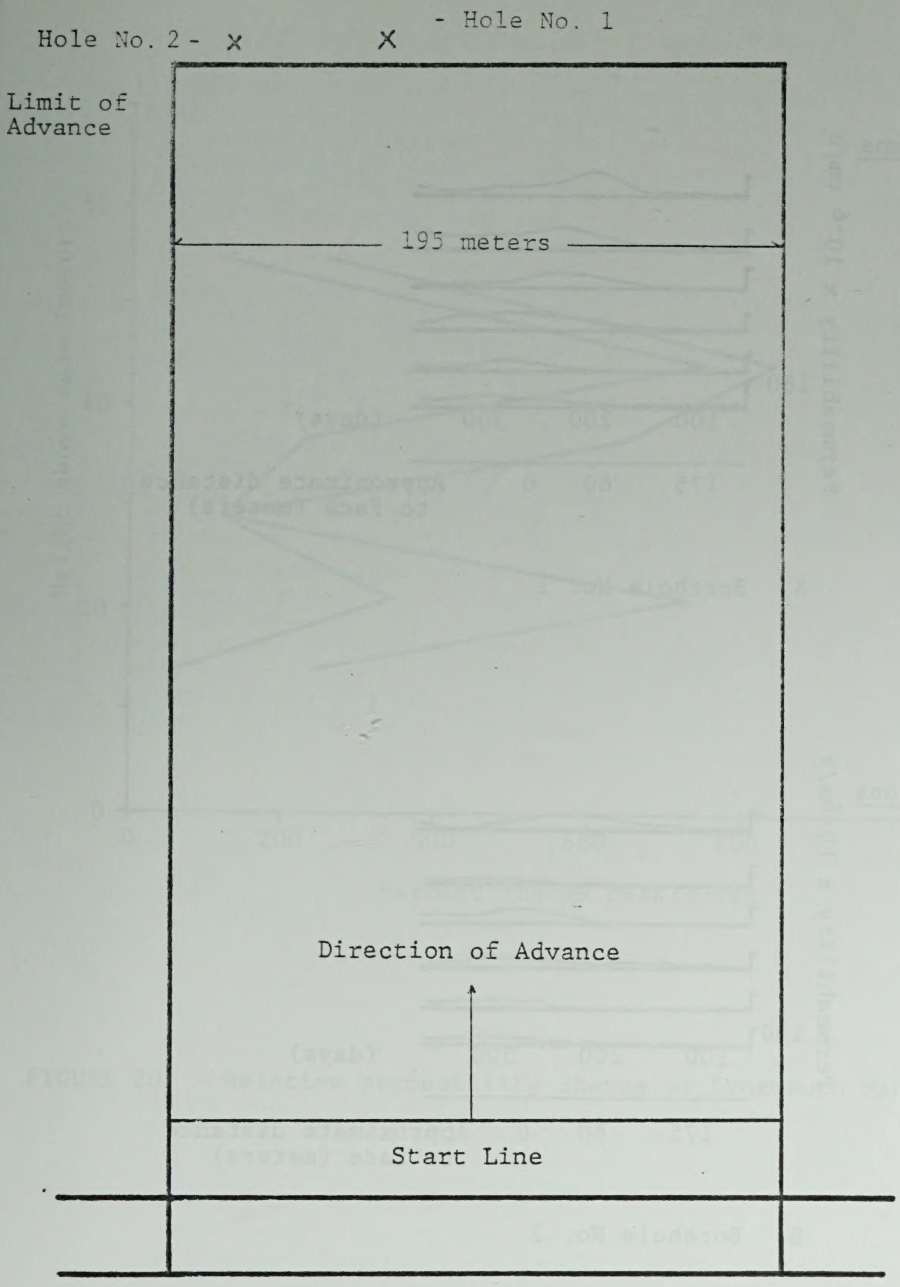
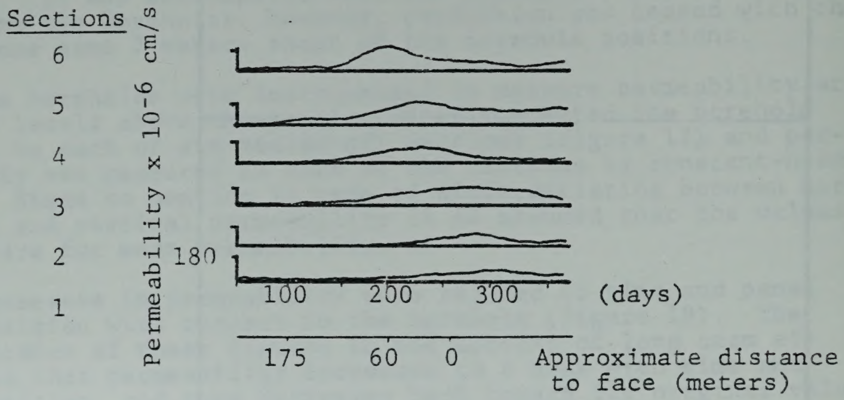
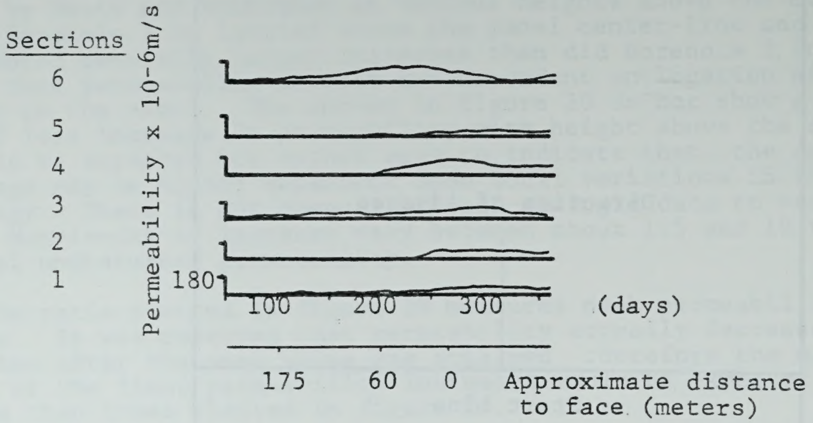


FIGURE 18. - Location of boreholes at Lynemouth Mine.



A. Borehole No. 1



B. Borehole No. 2

FIGURE 19. - Permeability versus time and distance to the longwall face at Lynemouth Mine.

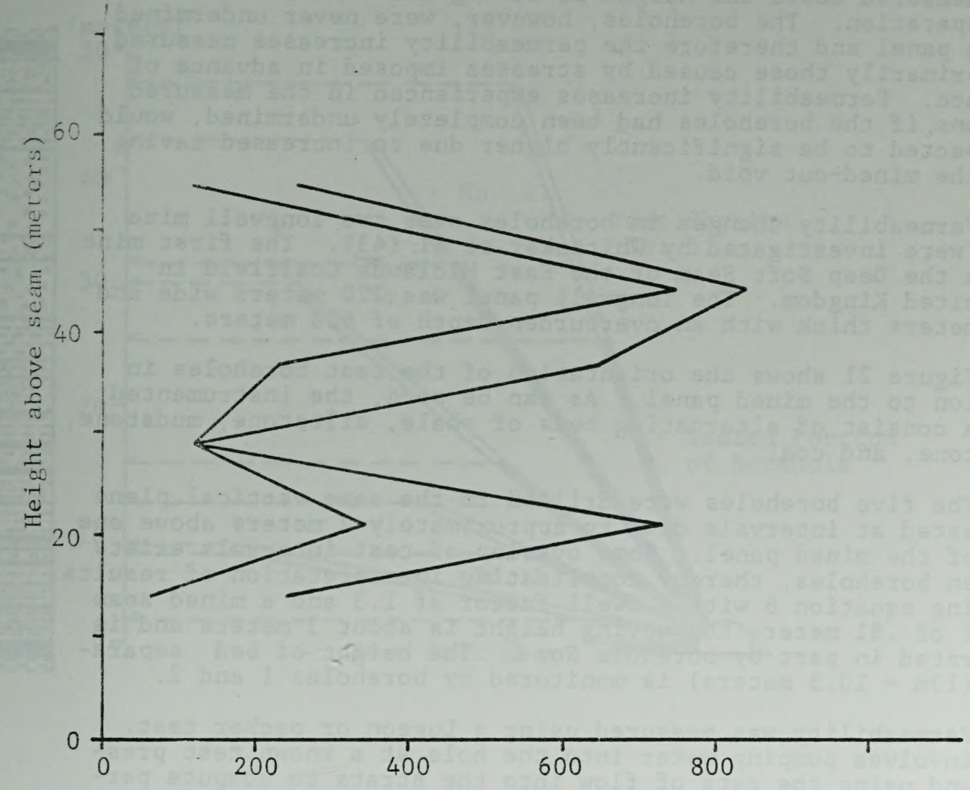


FIGURE 20. - Relative permeability change at Lynemouth Mine.

about 20 meters. The lowermost permeability changes were therefore measured above the height of caving and within the zone of bed separation. The boreholes, however, were never undermined by the panel and therefore the permeability increases measured were primarily those caused by stresses imposed in advance of the face. Permeability increases experienced in the measured sections, if the boreholes had been completely undermined, would be expected to be significantly higher due to increased caving into the mined-out void.

Permeability changes in boreholes over two longwall mine sites were investigated by Whittaker et al. (43). The first mine was in the Deep Soft Seam of the East Midlands Coalfield in the United Kingdom. The longwall panel was 220 meters wide and 0.81 meters thick with an overburden depth of 628 meters.

Figure 21 shows the orientation of the test boreholes in relation to the mined panel. As can be seen, the instrumented strata consist of alternating beds of shale, siltstone, mudstone, sandstone, and coal.

The five boreholes were drilled in the same vertical plane and tested at intervals down to approximately 2 meters above one edge of the mined panel. Some overlap of test intervals exists between boreholes, thereby complicating interpretation of results. Applying equation 8 with a swell factor of 1.3 and a mined seam height of .81 meters the caving height is about 3 meters and is penetrated in part by borehole No. 1 The height of bed separation (13m = 10.5 meters) is monitored by boreholes 1 and 2.

Permeability was measured using a Lugeon or packer test. This involves pumping water into the hole at a known test pressure and using the rate of flow into the strata to compute permeability. Higher flow rates correspond to higher permeabilities. Measurements were taken when the panel face was well away from the boreholes in order to establish a baseline permeability, and then periodically as the face advanced toward, under, and beyond the borehole locations.

Figure 22 shows the results for borehole Nos. 3 and 5. Whittaker et al. state that these results, "...show the flow characteristics before the ground was undermined together with test data showing the effect of undermining. The flow characteristics indicate the formation of widening cracks along the test cavity as the longwall face gradually undermined the test section." Figure 22B "...shows a test section which was only slightly affected by undermining (notice the change in abcissa scales); these results indicate that the ground became more impermeable before moving to a phase of increased permeability some distance after undermining." Orchard (12) noted that, "...deformation due to subsidence can increase the natural pressure in certain directions and insure a higher degree of imperm-

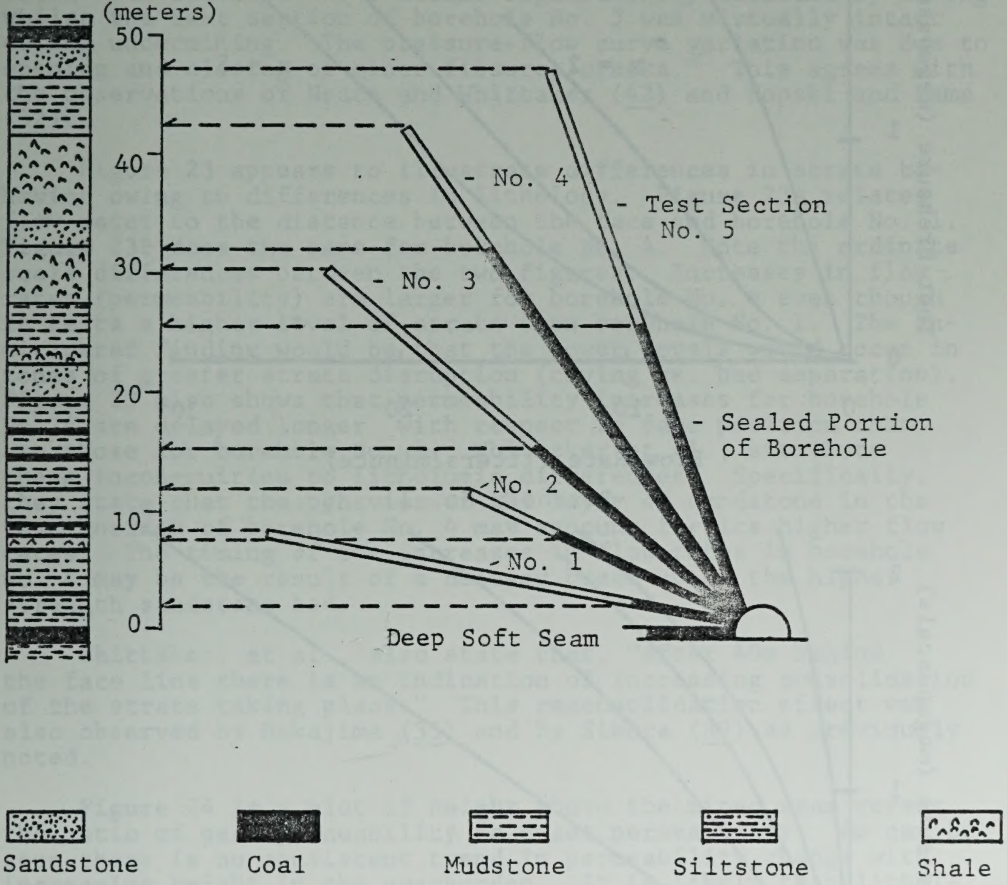
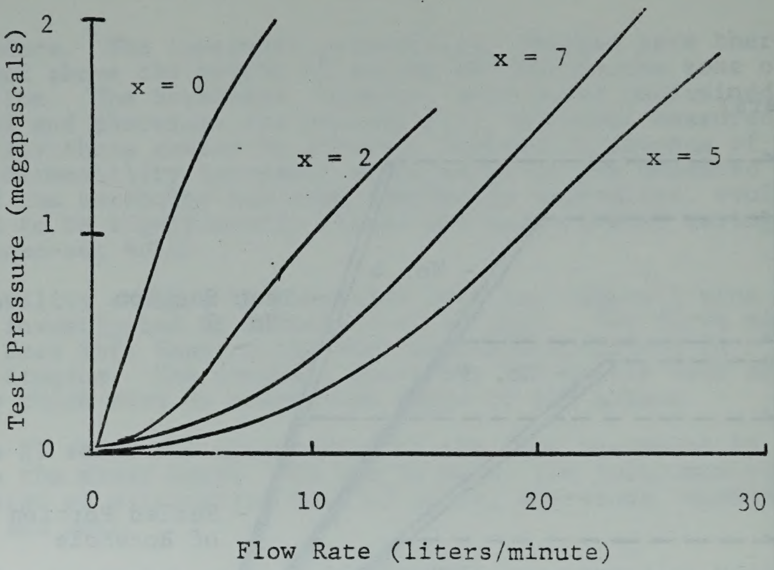
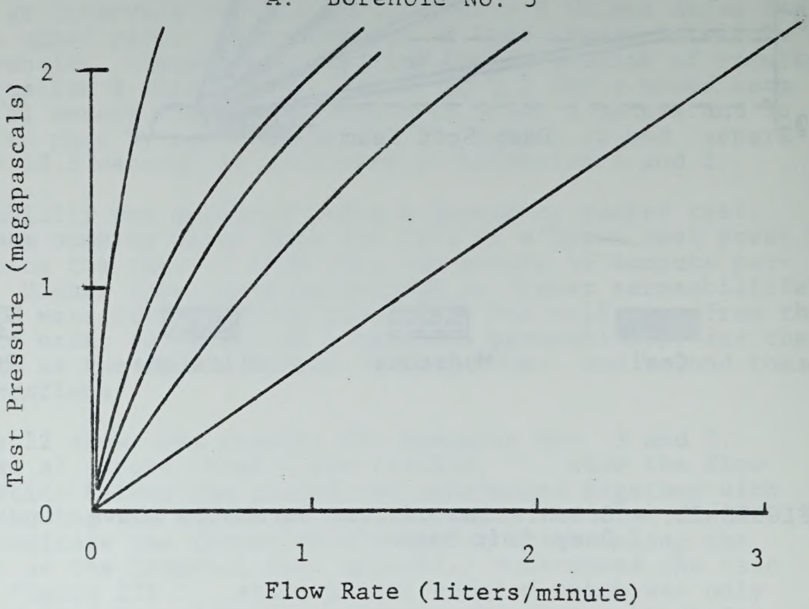


FIGURE 21. - Orientation of test boreholes above Deep Soft Seam.



A. Borehole No. 3



B. Borehole No. 5

FIGURE 22. - Borehole flow characteristics above Deep Soft Seam. x is the distance from the borehole to the face prior to (+x) and after (-x) undermining the borehole.

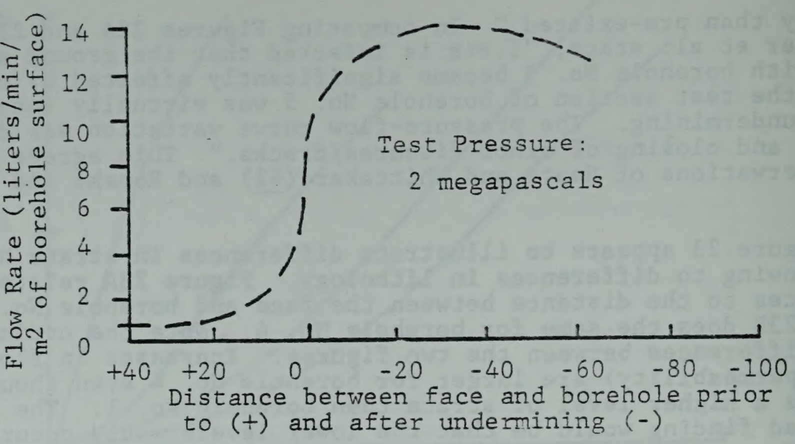
eability than pre-existed." In comparing Figures 22A and 22B Whittaker et al. state, "...it is inferred that the ground associated with borehole No. 3 became significantly affected by caving whilst the test section of borehole No. 5 was virtually intact during undermining. The pressure-flow curve variation was due to opening and closing of minor fissures/cracks." This agrees with the observations of Neate and Whittaker (42) and Ropski and Lama (32).

Figure 23 appears to illustrate differences in strata behavior owing to differences in lithology. Figure 23A relates flow rates to the distance between the face and borehole No. 1. Figure 23B does the same for borehole No. 4. Note the ordinate scale differences between the two figures. Increases in flow rates (permeability) are larger for borehole No. 4 even though it tests a higher level of strata than borehole No. 1. The anticipated finding would be that the lower levels would occur in zones of greater strata disruption (caving vs. bed separation). Figure 23 also shows that permeability increases for borehole No. 4 are delayed longer with respect to face position than are those for borehole No. 1. Whittaker et al., attribute these incongruities to lithologic differences. Specifically, they state that the behavior of the layer of sandstone in the test horizon of borehole No. 4 may account for its higher flow rates. The timing of the increases in flow rates in borehole No. 4 may be the result of a delayed break-up of the higher strength sandstone bed.

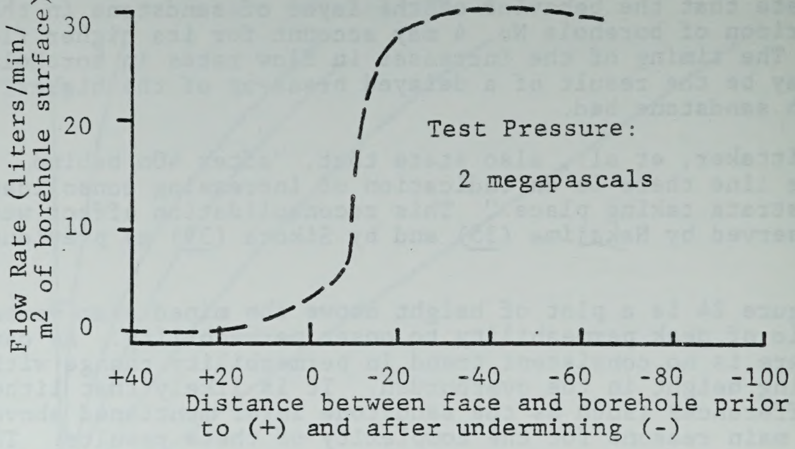
Whittaker, et al., also state that, "after 40m behind the face line there is an indication of increasing consolidation of the strata taking place." This reconsolidation effect was also observed by Nakajima (35) and by Sikora (39) as previously noted.

Figure 24 is a plot of height above the mined seam versus the ratio of peak permeability to onset permeability. As can be seen there is no consistent trend in permeability change with increasing height in the overburden. It is likely that lithologic differences (such as the sandstone layer mentioned above) are the main reasons for the complexity of these results. The magnitude of increase varies between about 9 and about 230 times the undisturbed permeability values.

The second site studied by Whittaker, et al., was a mine in the Swallow Wood seam of the Yorkshire Coalfield at Wentworth, England. The longwall extraction was 2.1 meters thick, 190 meters wide, and, 54 meters below the surface. Measurements were taken in an instrumented borehole drilled from the surface over the panel center line to a depth of 1.4 meters so that the lowermost tested interval was 13 to 14 meters above the mined panel. Given a swell factor of 1.3 and a mined thickness of 2.1 meters, the caving height for this mine is approximately



A. Borehole No. 1



B. Borehole No. 4

FIGURE 23. - Relationship between borehole flow characteristics and face position above Deep Soft Seam.

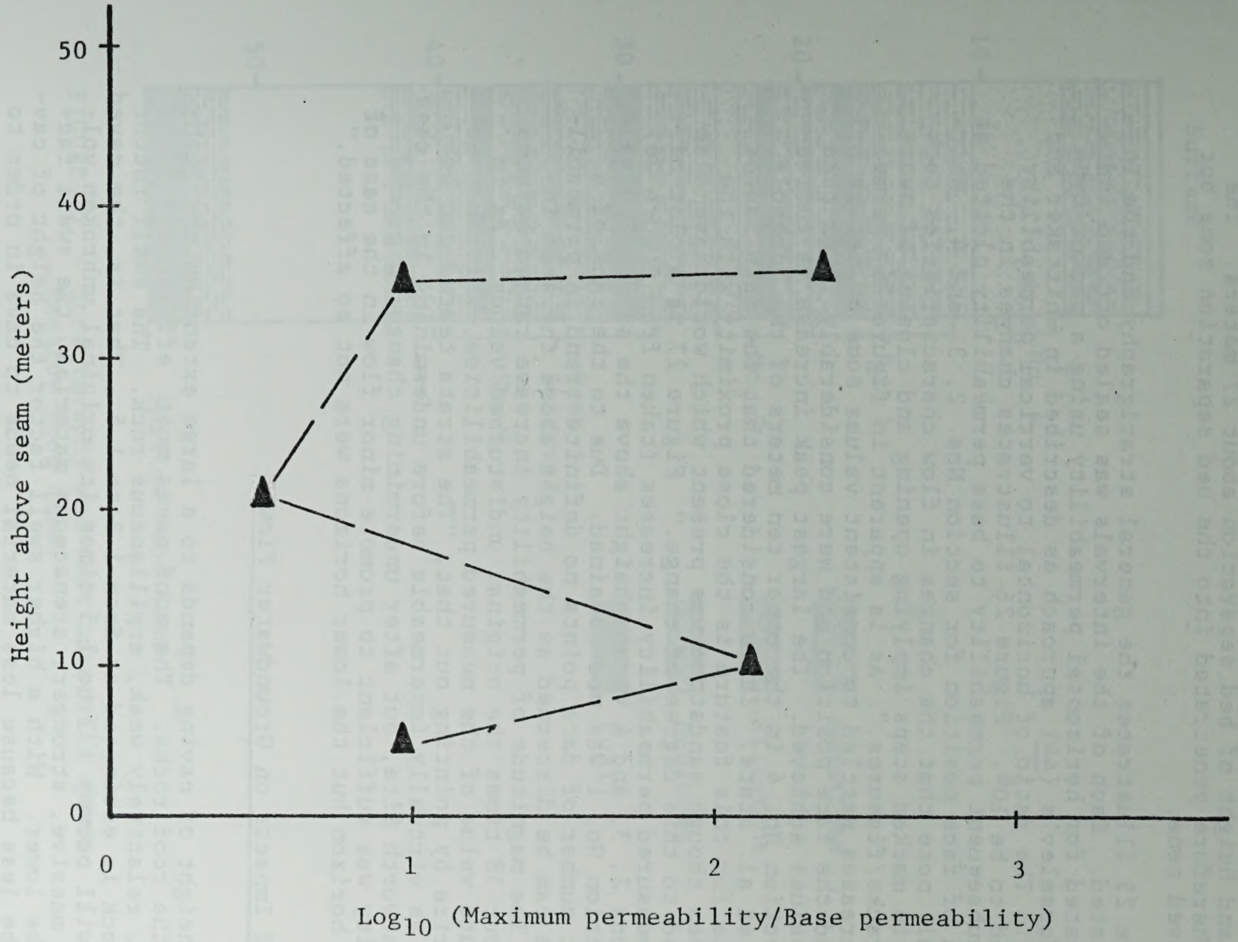


FIGURE 24. - Permeability changes with height above Deep Soft Seam.

7 meters, and height of bed separation about 27 meters. The borehole therefore penetrated into the bed separation zone but not the caved zone.

Figure 25 illustrates the general stratigraphy and the intervals tested. Each of the intervals was sealed off and individually tested for horizontal permeability using a packer-type test and Horselev's (44) approach as described in Whittaker and Singh (45). The ratio of horizontal to vertical permeability was assumed to be 10^6. Figure 26 illustrates changes in the ratio of subsequent permeability to base permeability plotted as a function of face position for section Nos. 2, 3, and 4. Whittaker et al. note that the changes in flow characteristics took place "...in marked steps implying opening and closing of near-surface cracks/fissures." As is apparent in figure 26, permeability increases settled to consistent values some 60 meters or more behind the face position and were considerably lower than the peak values achieved. The largest peak increase is indicated for section No. 4 in the upper ten meters of the borehole. Whittaker et al. state, "It is considered that the main factor responsible for this feature is the close proximity with the surface even though sandstone was present which would have also contributed to this degree of change." Figure 27 is a plot of the last measured permeability increases (taken from figure 26) for sections 2, 3, and 4 versus height above the seam. The value for section No. 1 was not obtained. Due to the lack of a sufficient number of data points no definite trend in permeability change can be discerned as the height above the seam increases. The magnitude of permeability increase ranged between 22 and about 38 times the original undisturbed values. As to the absolute value of the measured permeabilities, Whittaker et al. summarize by pointing out that, "The strata tested can be described as virtually impermeable before undermining in the case of the Wentworth Site, but after undermining change in ground permeability was sufficient to promote minor flow in the case of the upper horizon but the lower horizons were not so affected."

Summary of Impacts on Groundwater Flow

The height of caving depends to a large extent on the lithology of the roof rocks. The roof caves most efficiently if it is bedded, relatively weak, argillaceous rock. The swell factor of such rock is estimated at from 1.3 to 1.5. That is, the caved material will occupy 1.3 to 1.5 times its original unbroken volume. For massive, stronger, arenaceous material, the swell factor will be lower. With a higher swell factor the height of caving will be less because less material needs to cave in order to fill the mined void and provide support for the higher, unbroken strata. The swell factor of the roof material is accounted-for in equation 8(g) and equation 9(g_g). Equation 9 also takes into

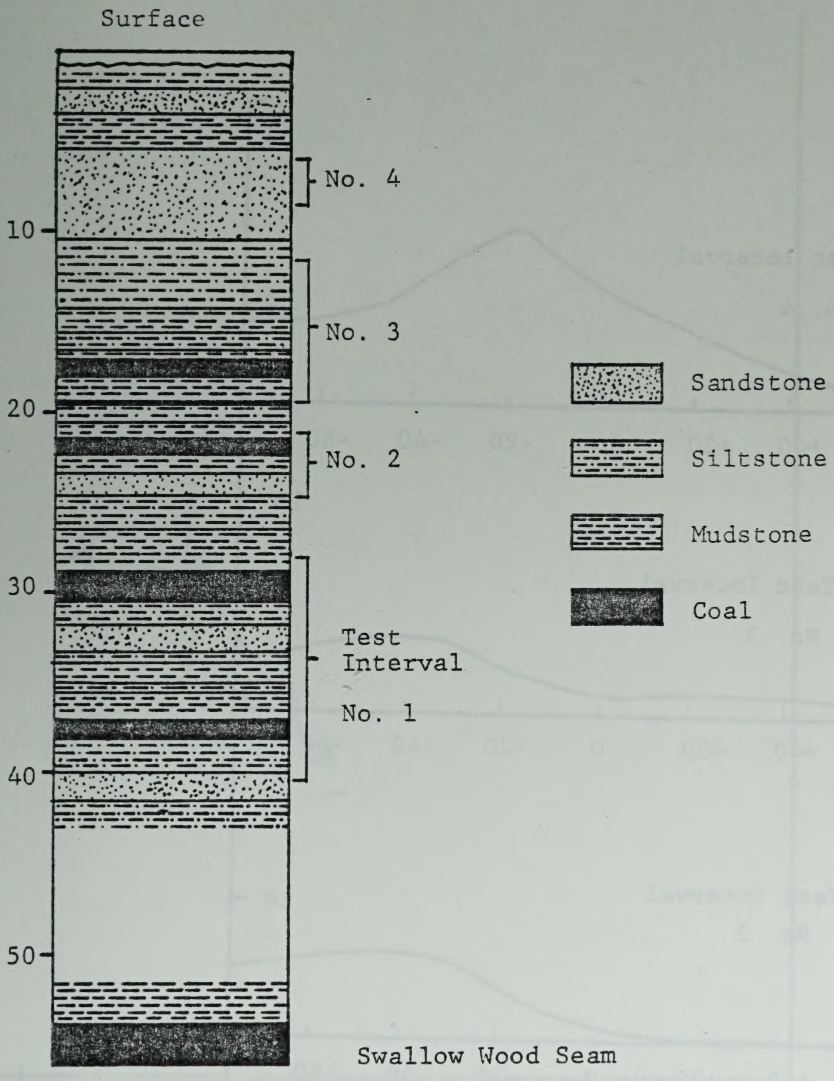


FIGURE 25. - Stratigraphy and test intervals above Swallow Wood Seam.

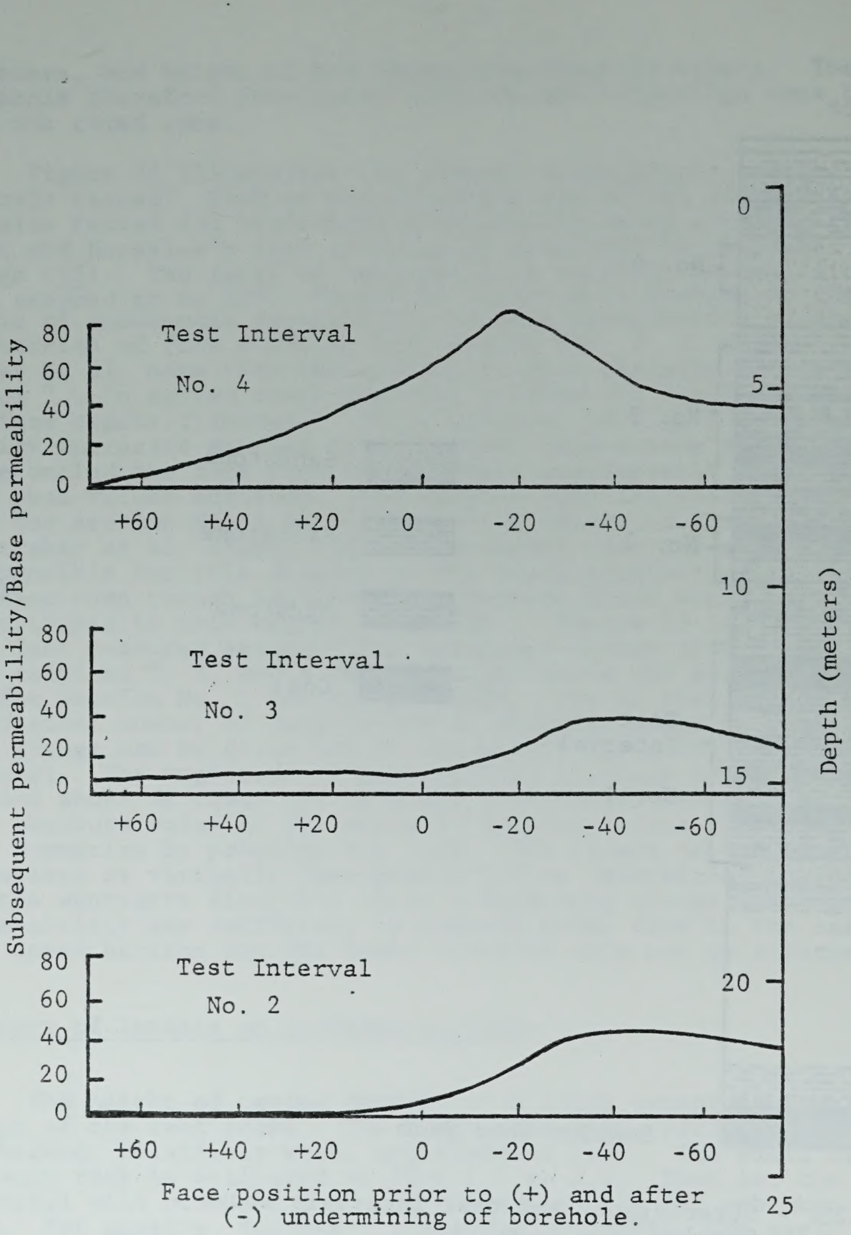


FIGURE 26. - Subsequent permeability/Base permeability versus face position for Swallow Wood Seam.

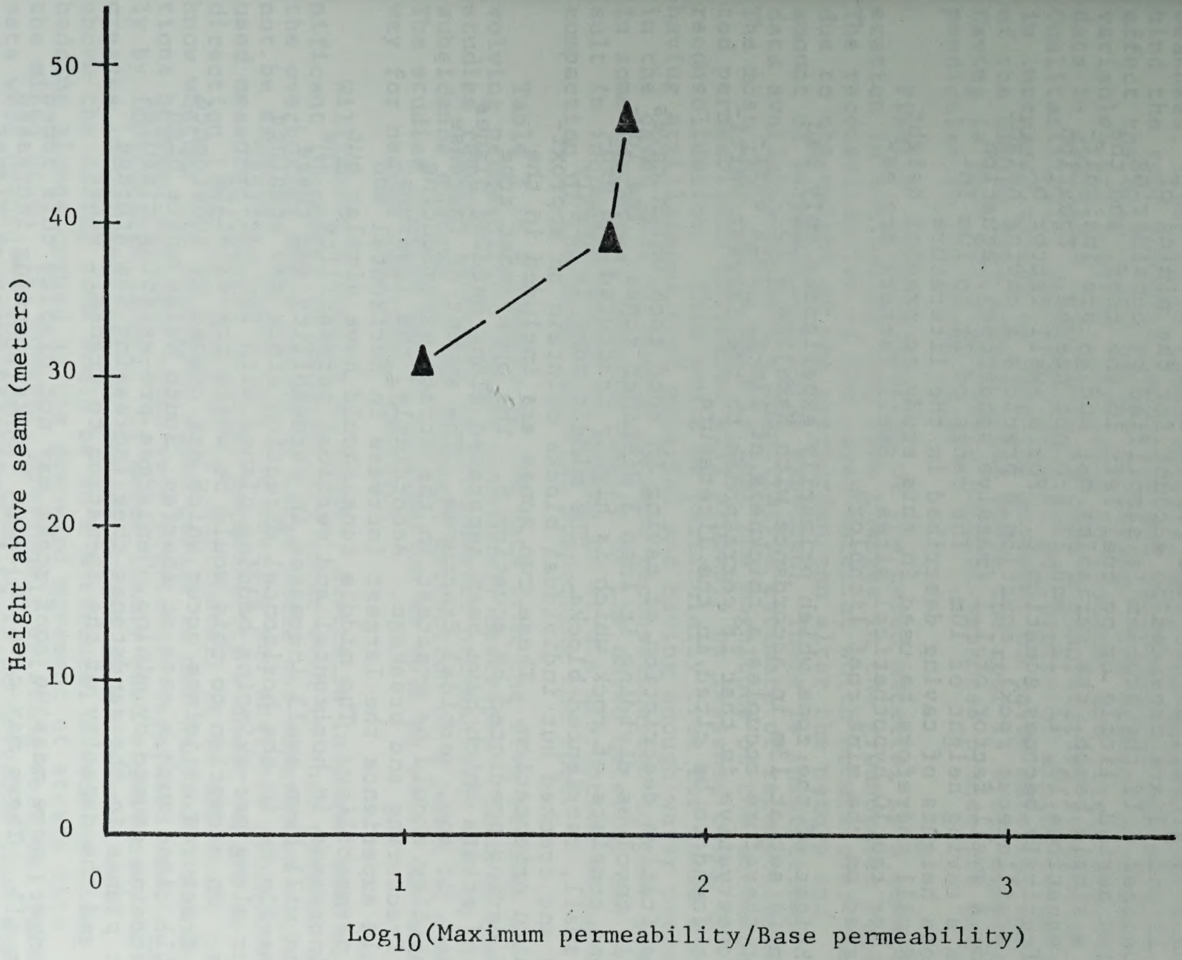


FIGURE 27. - Permeability changes with height above Swallow Wood Seam.

account the swell factor (g_p) and thickness (m_{pi}) of any coal left in the roof as well as the time (t) in days since mining. Equations 12 and 13 are provided to account for the mining of multiple benches. If the problem is simplified by considering a large time period, little or no coal left in the roof, and the mining of a single bench, the variables m_{pi} and g_p are insignificant and equations 10, 11, 12, and 13 are not needed. Equation 9 then effectively becomes equation 8. For a swell factor of 1.5 (weak argillaceous rock), equation 8 predicts a caving height of 2m. For a swell factor of 1.1 (massive sandstone), equation 8 predicts a caving height of 10m. The range of 2m to 10m includes those heights of caving described in the literature. Equation 8 will therefore be used in this study to predict height of caving for the 10 hypothetical sites. Swell factors are estimated based on the mine roof lithology.

The height of the zone which primarily experiences only bed separation is set at 13m in accordance with Nakajima's (35) study. It therefore occupies a thickness of 13m-C. This estimate is conservative in that it corresponds to the largest vertical extent found to be cited in the literature.

A qualitative description of caving in roof rock which caves efficiently involves dividing it into 3 distinct zones. The lowermost zone consists of rock which is highly fractured and broken into small, reoriented blocks. The middle zone is highly fractured and cracked but individual blocks maintain an approximate in situ orientation. These two zones are included in the height of caving predicted by equation 8. The upper-most zone consists of strata which have been separated along bedding planes but have few, if any, vertical fractures. The amount of increase in permeability should be greatest in the strata experiencing the most fracturing and breakage. Accordingly, the lowermost zone should experience the largest increase in horizontal and vertical permeability. The middle zone should have similar but smaller increases in horizontal and vertical permeability. The upper zone will have small increases in permeability and these will primarily be in the horizontal direction since new openings will occur along pre-existing bedding planes with few vertical fractures. An exception to this would be where pre-existing vertical fractures or joints occur which are opened by subsidence. Wardel (11) cites such a case at Aberfan, South Wales where high tensile strains caused by mining, "enlarges pre-existing fissures and joint planes in the sandstones thus increasing its storage capacity and the capacity of the formation to transmit water."

Stronger, more massive roof rocks may not display this zoned effect at all. These may cave in large blocks, causing increased permeability only along large, widely separated fracture planes and in voids created above the fractured material.

Variables such as the orientation of natural planes of weakness, flushing of caved material into the uncaved area behind the roof supports, and rate and uniformity of mining also affect the height and nature of caving. The effects of these variables are however, difficult to isolate, and little empirical data is available upon which to base a quantitative prediction. Qualitatitively, decreased rate of uniformity of mining results in increased caving as does the movement of caved material out of the caving area toward areas where the roof is still supported. Caving is most efficient where natural weakness planes are perpendicular to the mined face.

Finally, reconsolidation of the caved material is a consideration in evaluating long term changes in the groundwater regime. The reconsolidation of the caved material which occurs over time due to the weight of the overburden can alter the nature and amount of permeability to be expected. There is insufficient data available to make a quantitative estimate of reconsolidation. The most that can be said is that the magnitude of the anticipated permeability increases will probably be lessened owing to reconsolidation. This would be particularly true for those mines having argillaceous roof material and having enough water present in the caved goaf to enable optimum reconsolidation to take place. In some instances, reconsolidation of the caved material may result in increased height of caving or strata disruption owing to compaction of the caved material supporting the roof.

Table 3 is a summary of the data from the five studies involving permeability changes previously described. Each of the studies reports increases in groundwater permeability due to the subsidence effects of the longwall extraction of a panel of coal. The studies provide useful information as well as point out the way for needed additional research.

Williamson's results at Sydney, Australia indicate that significant increases in permeability occur even in that portion of the overburden where caving or large scale bed separation would not be expected. Given that the testing and analysis procedures used measured changes in total permeability without regard to direction (that is, vertical vs. horizontal) it is difficult to know whether the increases would result in new hydraulic connections between aquifers which were previously separated vertically by impermeable layers. It seems likely that significant increases in permeability for bedded strata at a distance well above the caving zone would be in a horizontal direction along bedding planes opened by the downward movement of strata into the mined void. If, however, previously existing vertical joint sets were opened by subsidence, then it is conceivable that considerable increases in vertical permeability might take place at this level.

TABLE 3. - Summary of case histories pertaining to permeability changes

Location	Height Above Seam (meters)	Post Mining/ Base Permeability	Lithology[1]	Mining Conditions
Sydney, Aust. (unworked)	0 - 383	~5	Thick SS's w/ thin CS & SH Layers	1.8 m Seam
Sydney, Aust. (worked)	63 - 273			340 m Overburden
Lynemouth (1)				
Interval 1	14 - 19	~4	SS, SH, C	1.5 m Seam 140 m Overburden 40 m Sea Water Previously worked horizons at and above datum level
" 2	19 - 27	~9	C, SH, SS	
" 3	27 - 34	~1.5	SS, SH, C	
" 4	34 - 42	~8	SS, C	
" 5	42 - 50	~10	SS, SH, C	
" 6	50 - 62	~4	C, SS, SH	
Lynemouth (2)				
Interval 1	14 - 19	~2	SS, SH, C	
" 2	19 - 27	~5	C, SH, SS	
" 3	27 - 34	~3	SS, SH, C	
" 4	34 - 42	~4	SS, C	
" 5	42 - 50	~8	SS, SH,C	
" 6	50 - 62	~2	C, SS, SH	

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[1] SS - Sandstone, SH - Shale, C - Coal, CS - Claystone, MS - Mudstone, SLS - Siltstone

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" 3	27 - 34	~1.5	SS, SH, C	
" 4	34 - 42	~8	SS, C	
" 5	42 - 50	~10	SS, SH, C	
" 6	50 - 62	~4	C, SS, SH	
Lynemouth (2)				
Interval 1	14 - 19	~2	SS, SH, C	
" 2	19 - 27	~5	C, SH, SS	
" 3	27 - 34	~3	SS, SH, C	
" 4	34 - 42	~4	SS, C	
" 5	42 - 50	~8	SS, SH,C	
" 6	50 - 62	~2	C, SS, SH	

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[1] SS - Sandstone, SH - Shale, C - Coal, CS - Claystone, MS - Mudstone, SLS - Siltstone

TABLE 3. - Summary of case histories pertaining to permeability changes (continued)

Location	Height Above Seam (meters)	Post Mining/ Base Permeability	Lithology[1]	Mining Conditions
Deep Soft				
Interval 1	2 - 8	~9	MS, SLS, SH	.81 m Seam
" 2	8 - 11	~136	SLS, MS	628 m Overburden
" 3	13 - 29	~3	MS, C, SH	
" 4	30 - 41	~228	SH, MS, SS	
" 5	25 - 45	~9	MS, SH, SS	
Swallow Wood				
Interval 1	13 - 26	NA	C, MS, SS, SLS	2.1 m Seam
" 2	29 - 32	~38	C, MS, SS, SLS	54 m Overburden
" 3	35 - 42	~22	SLS, MS, C	
" 4	46 - 48	~36	SS	

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Neate and Whittaker measured changes in permeability at the Lynmouth mine for levels of strata likely to be in and just above the zone of bed separation. They too, measured mean permeability and did not differentiate between vertical and horizontal permeability changes. They found that even though both measuring points were located over the mined panel, permeability changes were larger over the panel center line. Their findings also indicate that lithology has an overriding effect and that the magnitude of change does not necessarily decrease with increasing height above the seam as would be expected. A factor which must be considered in studying Neate and Whittaker's results is that the instrumented boreholes were never undermined during the period of data acquisition. The complete effects of subsidence were therefore not experienced.

Whittaker, et al., report the results of studies in two separate locations. Over the Deep Soft seam they measured changes in permeability in both the caved and bed separation zones. They too, found no recognizable trend in the magnitude of permeability increases as height above the seam increased and they attribute this to lithologic variations. They report increases of as much as 230 times the premining permeability. These are, however, peak values and their data indicates that permeability increases tend to peak during mining and then fall off to some lower value after mining is completed.

Data from the second site (Swallow Wood seam) studied by Whittaker, et al., provide information on changes in horizontal permeability in the bed separation zone and above. The results are reported to be, in part, a function of lithology and close proximity of the seam to the surface. The authors use 10^6 as the ratio of horizontal to vertical permeability. Application of this ratio to the largest amount of horizontal permeability measured after mining gives a value of vertical permeability on the order of 10^{-11} cm/sec. This would be typical of a virtually impermeable clay. It would seem, then, that increases in vertical permeability in the zone tested by Whittaker, et al., (that is, the bed separation zone and above) were in this case insignificant in terms of establishing new hydraulic connections between layers of overlying strata.

All three studies show that permeability increases do take place within subsided strata. Orders of magnitude of the increases spanned a wide range and were complicated by the unknown relationship between horizontal and vertical permeability and by local variables such as lithology. In order to make quantitative predictions of permeability increases for a given mine, much more empirical data must be acquired on which to base a methodology. While no quantitative methodology can be derived from the three studies cited, it can be safely concluded that, at least for the strata located in the caving or bed separation zones, the potential exists for large order of magnitude increases in permeability and therefore for the establishment of hydraulic connections between previously isolated aquifers.

Impacts on Groundwater Quality

In a search of the literature, no case history studies were found which specifically dealt with measured water quality changes associated with the underground total extraction of thick coal seams. In any case, it is doubtful whether a useful methodology for predicting changes in water quality parameters in the western United States could be developed from the empirical data of foreign case histories. Most of the areas in foreign countries where underground thick seam mining is taking place exhibit significant differences in the conditions of climate, lithology and groundwater from those found in the western United States. For example, Musser (46) cites three factors responsible for the generation of acid mine drainage:

(1) The presence of considerable amounts of pyrite;

(2) abundant rainfall and runoff; and

(3) low natural alkalinity of the groundwater being affected.

All of these factors are often present in European coalfields. In the western United States, however, the arid to semiarid conditions, low sulfer (pyrite) coal, and normally alkaline nature of the groundwater tend to minimize the occurence of acid mine drainage.

Similarities in process do, however, occur between western United States and foreign coal fields in terms of the physical effects of underground longwall mining on the groundwater media. This is important because the quality of groundwater is determined largely by the nature of the media through which it flows. Hamilton and Wilson (47) point out that, "In an aquifer, with slow water movement and a large surface area for the liquid-solid interface, there is a long contact period which allows the establishment of a chemical equilibrium between the liquid and solid phases. Consequently, water tends to exhibit chemical characteristics imparted to it by the media it has flowed through. Thus, water taken from different aquifer materials will have different chemical compositions." It follows then, that a change rendered to the media by mining activity will have an effect on groundwater quality.

In the case of the total underground extraction of thick seams, the media will be altered in primarily two ways:

(1) The replacement of part of the coal seam aquifer by caved overburden material; and

(2) the creation of a previously nonexistent hydraulic connection between two aquifers containing groundwater of differing quality.

The replacement of part of a coal seam by caved overburden material is especially significant for western United States coal fields because oftentimes the coal seams themselves serve as the most important confined aquifer in the shallow groundwater system. This has been pointed out by Van Voast and Hedges (48), and Davis (49). It has also been confirmed by studies done by Hittman Associates (50) in the Powder River Basin of Wyoming and Montana (an area where many seams in excess of 15 feet thick are present). Groundwater flowing through the fractures in organic coal material tends to be less mineralized and therefore of a higher quality than water obtained from inorganic aquifers. The replacement of organic coal by inorganic materials which have been fractured exposing fresh mineral surfaces to solution and oxidation, therefore, tends to decrease water quality.

Van Voast, et al., (51) studied the quality of water associated with several large strip mines in the Powder River Basin of Montana. Groundwater from spoil material was studied to discern changes in quality. Spoil material is, in fact, overburden which has been used to fill the void created by strip mining a coal seam. In that it has replaced part of the water-bearing seam it is the surface mine equivalent of the caved material in an underground longwall mine. Van Voast, et al., found that the chemical quality of the post-mining groundwater was highly dependent upon the amount and types of soluble salts in the spoil material. They also found that the, "Spoil waters from individual mines are of the same general chemical types as are the ground waters from nearby undisturbed aquifers." In general, they noted that the median concentrations of dissolved solids and of some trace elements are higher in waters from mine spoil than in waters from coal beds. They felt that the potential for increased dissolved solids was most significant.

Hounslow, et al., (52) studied the relationship between overburden mineralogy and groundwater chemical changes at six surface mines in Wyoming, Colorado, New Mexico and Montana. They encountered sandstones, siltstones, shales, and limestones in the overburden material. In terms of effects on water quality, the critical minerals found within these rock types were sulfates, carbonates, clays, and sulfides. Gypsum was found to be the most important sulfate because it is readily soluble in water and is probably the major contributer of Ca and SO_4. Calcite was the most important carbonate mineral because it can be dissolved by dilute acids such as the sulfuric acid produced by the oxidation of pyrite. Calcite generally occured as a cementing agent in sandstones and siltstones. Dolomite was also present at most of the mines and although less soluble than calcite, can be dissolved by sulfuric acids. Among the sulfides, "Pyrite (FeS) is the most common sulfide occurring in the overburden rocks and in the coal of the mines studied.

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" 4	46 - 48	~36	SS	

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Neate and Whittaker measured changes in permeability at the Lynmouth mine for levels of strata likely to be in and just above the zone of bed separation. They too, measured mean permeability and did not differentiate between vertical and horizontal permeability changes. They found that even though both measuring points were located over the mined panel, permeability changes were larger over the panel center line. Their findings also indicate that lithology has an overriding effect and that the magnitude of change does not necessarily decrease with increasing height above the seam as would be expected. A factor which must be considered in studying Neate and Whittaker's results is that the instrumented boreholes were never undermined during the period of data acquisition. The complete effects of subsidence were therefore not experienced.

Whittaker, et al., report the results of studies in two separate locations. Over the Deep Soft seam they measured changes in permeability in both the caved and bed separation zones. They too, found no recognizable trend in the magnitude of permeability increases as height above the seam increased and they attribute this to lithologic variations. They report increases of as much as 230 times the premining permeability. These are, however, peak values and their data indicates that permeability increases tend to peak during mining and then fall off to some lower value after mining is completed.

Data from the second site (Swallow Wood seam) studied by Whittaker, et al., provide information on changes in horizontal permeability in the bed separation zone and above. The results are reported to be, in part, a function of lithology and close proximity of the seam to the surface. The authors use 10^6 as the ratio of horizontal to vertical permeability. Application of this ratio to the largest amount of horizontal permeability measured after mining gives a value of vertical permeability on the order of 10^{-11} cm/sec. This would be typical of a virtually impermeable clay. It would seem, then, that increases in vertical permeability in the zone tested by Whittaker, et al., (that is, the bed separation zone and above) were in this case insignificant in terms of establishing new hydraulic connections between layers of overlying strata.

All three studies show that permeability increases do take place within subsided strata. Orders of magnitude of the increases spanned a wide range and were complicated by the unknown relationship between horizontal and vertical permeability and by local variables such as lithology. In order to make quantitative predictions of permeability increases for a given mine, much more empirical data must be acquired on which to base a methodology. While no quantitative methodology can be derived from the three studies cited, it can be safely concluded that, at least for the strata located in the caving or bed separation zones, the potential exists for large order of magnitude increases in permeability and therefore for the establishment of hydraulic connections between previously isolated aquifers.

Impacts on Groundwater Quality

In a search of the literature, no case history studies were found which specifically dealt with measured water quality changes associated with the underground total extraction of thick coal seams. In any case, it is doubtful whether a useful methodology for predicting changes in water quality parameters in the western United States could be developed from the empirical data of foreign case histories. Most of the areas in foreign countries where underground thick seam mining is taking place exhibit significant differences in the conditions of climate, lithology and groundwater from those found in the western United States. For example, Musser (46) cites three factors responsible for the generation of acid mine drainage:

(1) The presence of considerable amounts of pyrite;

(2) abundant rainfall and runoff; and

(3) low natural alkalinity of the groundwater being affected.

All of these factors are often present in European coalfields. In the western United States, however, the arid to semiarid conditions, low sulfer (pyrite) coal, and normally alkaline nature of the groundwater tend to minimize the occurence of acid mine drainage.

Similarities in process do, however, occur between western United States and foreign coal fields in terms of the physical effects of underground longwall mining on the groundwater media. This is important because the quality of groundwater is determined largely by the nature of the media through which it flows. Hamilton and Wilson (47) point out that, "In an aquifer, with slow water movement and a large surface area for the liquid-solid interface, there is a long contact period which allows the establishment of a chemical equilibrium between the liquid and solid phases. Consequently, water tends to exhibit chemical characteristics imparted to it by the media it has flowed through. Thus, water taken from different aquifer materials will have different chemical compositions." It follows then, that a change rendered to the media by mining activity will have an effect on groundwater quality.

In the case of the total underground extraction of thick seams, the media will be altered in primarily two ways:

(1) The replacement of part of the coal seam aquifer by caved overburden material; and

(2) the creation of a previously nonexistent hydraulic connection between two aquifers containing groundwater of differing quality.

The replacement of part of a coal seam by caved overburden material is especially significant for western United States coal fields because oftentimes the coal seams themselves serve as the most important confined aquifer in the shallow groundwater system. This has been pointed out by Van Voast and Hedges (48), and Davis (49). It has also been confirmed by studies done by Hittman Associates (50) in the Powder River Basin of Wyoming and Montana (an area where many seams in excess of 15 feet thick are present). Groundwater flowing through the fractures in organic coal material tends to be less mineralized and therefore of a higher quality than water obtained from inorganic aquifers. The replacement of organic coal by inorganic materials which have been fractured exposing fresh mineral surfaces to solution and oxidation, therefore, tends to decrease water quality.

Van Voast, et al., (51) studied the quality of water associated with several large strip mines in the Powder River Basin of Montana. Groundwater from spoil material was studied to discern changes in quality. Spoil material is, in fact, overburden which has been used to fill the void created by strip mining a coal seam. In that it has replaced part of the water-bearing seam it is the surface mine equivalent of the caved material in an underground longwall mine. Van Voast, et al., found that the chemical quality of the post-mining groundwater was highly dependent upon the amount and types of soluble salts in the spoil material. They also found that the, "Spoil waters from individual mines are of the same general chemical types as are the ground waters from nearby undisturbed aquifers." In general, they noted that the median concentrations of dissolved solids and of some trace elements are higher in waters from mine spoil than in waters from coal beds. They felt that the potential for increased dissolved solids was most significant.

Hounslow, et al., (52) studied the relationship between overburden mineralogy and groundwater chemical changes at six surface mines in Wyoming, Colorado, New Mexico and Montana. They encountered sandstones, siltstones, shales, and limestones in the overburden material. In terms of effects on water quality, the critical minerals found within these rock types were sulfates, carbonates, clays, and sulfides. Gypsum was found to be the most important sulfate because it is readily soluble in water and is probably the major contributer of Ca and SO4. Calcite was the most important carbonate mineral because it can be dissolved by dilute acids such as the sulfuric acid produced by the oxidation of pyrite. Calcite generally occured as a cementing agent in sandstones and siltstones. Dolomite was also present at most of the mines and although less soluble than calcite, can be dissolved by sulfuric acids. Among the sulfides, "Pyrite (FeS) is the most common sulfide occurring in the overburden rocks and in the coal of the mines studied.

Although ubiquitous, it is present only in small amounts. Oxidation of pyrite releases sulfuric acid which, in an unbuffered system, causes a drastic decrease in pH, and which in turn results in the well-known acid mine drainage. With limited amounts of pyrite and excess calcite and/or dolomite, as occurred in all the sites studied, the acid is neutralized and Ca, Mg, and sulfate are added to the water. The iron (from the pyrite) is precipitated as amorphous ferric hydroxide." The presence of clays was found to be significant because they preferentially absorb heavy elements and release lighter ones, "thereby tending to act as chemical sponges exchanging and absorbing undesirable heavey metals and releasing less toxic ones". Hounslow, et al., reach the following conclusions.

(1) Spoil waters were generally calcium-magnesium-sulfate waters, high in total dissolved solids (TDS).

(2) The carbonate-sulfide ratio controlled the pH.

(3) Magnesium enrichment may result from gypsum precipitation.

(4) Heavy metals are generally absent due to absorption by clays.

As is noted above, the oxidation of pyrite produces sulfuric acid. Sulfuric acid and the carbonic acid naturally present in precipitation react with calcium, magnesium, aluminum and manganese minerals to produce soluble sulfates and increase TDS. So while pyrite oxidation and atmospheric weathering do not produce acid mine drainage in western coal fields, they do contribute to the increase in total dissolved solids.

Acid formation requires the presence of both water and air. Water serves as both a transport vehicle and a reactant in the oxidation process, but oxidation reactions are drastically slowed when there is no air present to provide oxygen. Hill (28) notes that several investigators have found that when pyrite is submerged under water, pyrite oxidation essentially ceases.

The subsidence process over a longwall mine would be expected to open fractures and fissures above the mined void and thereby permit more air to enter into the caved area. Since, however, total extraction mining results in caved material filling the mined area, no large open voids will be left through which air may pass easily. In instances where the mined seam serves as an aquifer, water would be expected to fill the interstices of the caved material and further reduce the possibility of air contacting oxidizable minerals. In addition, unlike spoil material in a surface mine, the caved material of an underground longwall-type mine does not have direct contact with the atmosphere. Consequently, wind currents and molecular diffusion (the movement of oxygen from the air near the surface of the spoil, where concentration is higher, to the gas or liquid-filled pores within the spoil, where it is lower) do not have an opportunity to increase pyrite oxidation by supplying more oxygen. For these reasons it would be expected that the magnitude of change in water quality owing to the exposure of fresh mineral surfaces to oxidation and solution would most likely be less for total extraction underground mines than for room and pillar or surface mines. While magnitudes would decrease however, the chemical changes should be similar in nature to those described by Hounslow et al. (52).

The second physical change to the groundwater environment which could have a significant effect on groundwater quality is the creation, through fracturing of the roof rock, of a hydraulic connection between two previously isolated aquifers. Mixing of water through this connection would give the resulting water a quality level approaching some average value. The largest changes should be a result of mixing waters which are the furthest apart in comparative quality. Normally, the greatest differences in water quality for groundwater in the western United States is found in comparing organic coal seam aquifer water to inorganic overburden aquifer water, usually sandstone. Therefore the greatest potential for change in water quality by the mixing of previously separated groundwater, comes when the fracture zone above a mined coal seam intercepts an overlying sandstone aquifer, causing its water to migrate into the caved material and mix with the higher quality coal seam water.

Summary of Impacts on Groundwater Quality

Given the factors of an arid to semiarid climate, low amounts of naturally occurring sulphides (pyrite), and alkaline groundwater, acid mine drainage should not be a problem for western longwall mines. Caving of overburden into the mined void will expose fresh fracture surfaces to oxidation and solution, creating the possibility of locally higher TDS in the water flowing in a coal seam aquifer. Fracturing of an overburden aquifer may result in a slight decrease in water quality through the exposure of fresh mineral surfaces but it is likely that the effects will be negligible since the groundwater will not be exposed to any significantly different lithology. Overall, the deleterious effects on water quality of replacing the mined coal with caved material in a longwall thick-seam mine should not be as great, and in most cases less than the effects from room and pillar or surface strip mining.

The creation of hydraulic connections between previously isolated aquifers and the resulting mixing of their waters will cause local changes in quality towards some average value. This could be a serious water quality problem when unpotable water is allowed to enter an aquifer system used for domestic water supply.

Development of a methodology for predicting impacts on groundwater quality based upon foreign case histories is not possible at this time due to widely differing environments and a paucity of data. Development of a methodology based on domestic data also suffers from a paucity of data and is beyond the scope of this study. Potential for water quality changes is however, noted in the site analysis wherever there is sufficient information to permit it.

SECTION V

ANALYSIS OF TEN STUDY SITES

Site Selection and Analysis

Ten study sites from the identified thick-seam fields were chosen for further analysis. The intent was to select sites which would provide a wide range of surface and groundwater hydrology, overburden lithology and geology, topography, and climate. Since these factors are similar for many of the identified fields, particularly for those fields in the Powder River Basin, the range of selection was somewhat limited. Sites were chosen in each of the states shown to contain thick-seam fields and this resulted in the largest variability possible. In addition, wide ranges of overburden depths and extracted seam thicknesses were chosen in order to provide variability in the subsidence geometry. The specific locations of the hypothetical longwall mines were dependent upon the data available for the field. In many instances the information used to confirm the presence of a mineable thick seam was from drill holes or outcrops in areas of relatively shallow overburden. In these cases the seams were projected into areas of thicker overburden which would be more suitable for underground mining and which would enable a wider range of mine geometries to be analyzed. Since the purpose was to assess impacts on existing water resources an effort was also made to locate sites where significant ground or surface water was present. Within each site single panels were located and their impacts analyzed in addition to and separate from the square mile site as a whole. Emphasis was place on locating these single panels within the site at places where the most potential for disruption to hydrology occured. They may or may not be the first panels mined at a particular site and their orientation was determined with reference to hydrologic considerations rather than mining efficiency considerations.

The analyses are limited by the amount of data available for each of the study sites and by the case history data found in the foreign literature search. The scope of the study did not permit field work or an extensive site by site search for and analysis of such data as detailed lithologic and geophysical borehole logs, pump tests, streamflow records and stream hydrographs, precipitation records and rock properties tests. The following factors are pertinent to the analyses.

(1) The data sheets for each single panel and each square mile site show calculations for maximum subsidence and the subsidence profile using

both the Subsidence Engineers' Handbook (4) and equation 1 by Kumar and Singh (1).

(2) For the sake of simplicity it was necessary to assume that the entire seam is extracted, leaving no barrier pillars under the square mile sites. Given present day technology, this assumption is somewhat unrealistic. If panels of equal widths and thicknesses were mined leaving barrier pillars between them, it would be expected that the subsidence characteristics above them would vary with overburden depth since the width-depth ratio for each individual panel would not necessarily be critical. To provide a feel for the amount of variation to be expected, the site maps delineate overburden thicknesses above and below the median thickness.

(3) A standard panel width of 180 meters was used for all single panels. Although panel length is depicted, its exact value is left undetermined but assumed to be sufficient to ensure that, $L \geq 1.4h$. In all ten cases this is a realistic assumption.

(4) Based on case history data, a limit angle (ζ) of 16 degrees was chosen for defining D, the distance on the surface from the panel centerline to the point where subsidence is zero, in Kumar and Singh's equation 1.

(5) The ratio of maximum subsidence found by Kumar and Singh in the Indian coal fields, S_{KS}, to maximum subsidence predicted by the Subsidence Engineers' Handbook, S_{SEH}, was found to be .65. Therefore, in equation 1, $S_m = S_{KS} = .65\ S_{SEH}$.

(6) The minimum overburden depth above the panel was used to calculate subsidence and strain for the single panels. This constitutes a conservative approach for predicting subsidence in that for a given panel width, maximum subsidence tends to be greater as overburden depth (h) decreases (see figure 3). Equation 5 indicates that strain can also be expected to increase with decreasing h.

(7) The median overburden depth at the site was used to calculate subsidence and strain over the entire square mile site.

(8) Since it was assumed that all of the coal under the square mile was extracted, leaving no barrier pillars, the mile width of the sites ensured that the critical width was always exceeded and maximum possible subsidence (S_m) was always the case. For the analysis of the square mile area, critical width, w_c, was deter-

mined by entering figure 3 with the overburden depth and projecting to the x = 0.9 line. The critical width is then read off and used to compute w_c/h. w_c/h is used in order to fall within the range of width - depth ratios given in figures 5 and 9.

(9) The data sheets show calculations for maximum tensile strains and the strain profiles using the Subsidence Engineers' Handbook.

(10) The subsidence and strain full profiles are plotted for each of the single panels and each of the square mile sites.

(11) The comparison of the subsidence profile generated from the Subsidence Engineers' Handbook to that generated by equation 1 depicts the range of subsidence to be expected for the given mine geometry between areas of weak overburden lithology (SEH) and areas of strong overburden lithology (KS).

(12) The ground surface width defined by projections from the points of intersection of the 5 mm/m strain line with the strain profile represents that width over which surface fissures are most likely to occur.

(13) Computations for maximum slope along the subsidence profile, G, and for height of expected caving, C, are also included on the data sheets.

(14) Swell factors were estimated according to overburden lithology. In all cases swell factors were found to be lower than for the easier caved, weaker rocks of the British Coal Measures.

(15) Finally, it should be noted that the locations of some of the strata disruptions are transitory and depend upon the location at a particular point in time of the mining activities and their associated subsidence. This is particularly true for surface water impacts since they occur to a large extent in the zone of greatest profile curvature towards the outer edges of the subsided area. For instance, fissures which have opened above the edge of a trough may later close when the mining of a neighboring panel (leaving no barrier pillars) effectively moves the edge to a new location.

Following are the detailed analyses of each of the ten selected study sites in thick seam coal fields of the western United States.

North Park Field

Mine Data (Single Panel)

Seam Name: Suddeth

Extracted Seam Height, m = 4.57 m
Minimum Overburden Depth, h = 457 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 0.39
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = 0.35
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 1.44$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.07	.14	.29	.43	.58	.72	.86	1.01	1.15	1.30	1.37	1.44
Distance as d/h	.90	.60	.48	.35	.29	.24	.21	.18	.15	.12	.08	.06	0
Distance (d) in Meters	409	272	217	158	130	110	96	82	69	55	37	27	0

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = .94$ m

D = 221 m

Distance (d) in Meters	221	203	184	166	147	129	111	92	74	55	37	19	1
Subsidence (s) in Meters	0	.02	.09	.18	.29	.41	.53	.64	.74	.82	.88	.92	.94

Strain

Multiplier = 1.75
S_{SEH}/h = .0031
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 5.4 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	1.1	2.2	3.2	4.3	5.4	4.3	0
Distance as d/h	.89	.61	.53	.45	.41	.32	.28	0
Distance (d) in Meters	407	279	242	206	187	146	128	0

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.0087

Height of Caving, C = m/g - 1 = 23 m

Results

Small surface strains, +E = 5.4 mm/m, are experienced over this mine owing to a low subsidence to overburden ratio, S/h = .0031. The possibility of surface fissures occuring is therefore minimal. Vertical settlement, S_{SEH} = 1.44 m, and slope change, G = .0087, are also small. The impacts on Bostwick Ditch should therefore be small. The low gradient of the ditch may however, cause some ponding to occur. Flow through the ditch may also be affected because the lateral extent of the subsidence is fairly large and may overlap the bend in the ditch along the panel's southwest side.

Height of caving, C = 23 m, is not extensive and coupled with the fact that the strata dips fairly steeply into the subsurface, indicates that groundwater impacts will not be large. Surface water is relatively abundant in North Park, reducing the necessity for deep wells. Most groundwater is produced from shallow alluvium and glacial material which is unlikely to be significantly impacted by underground mining activities.

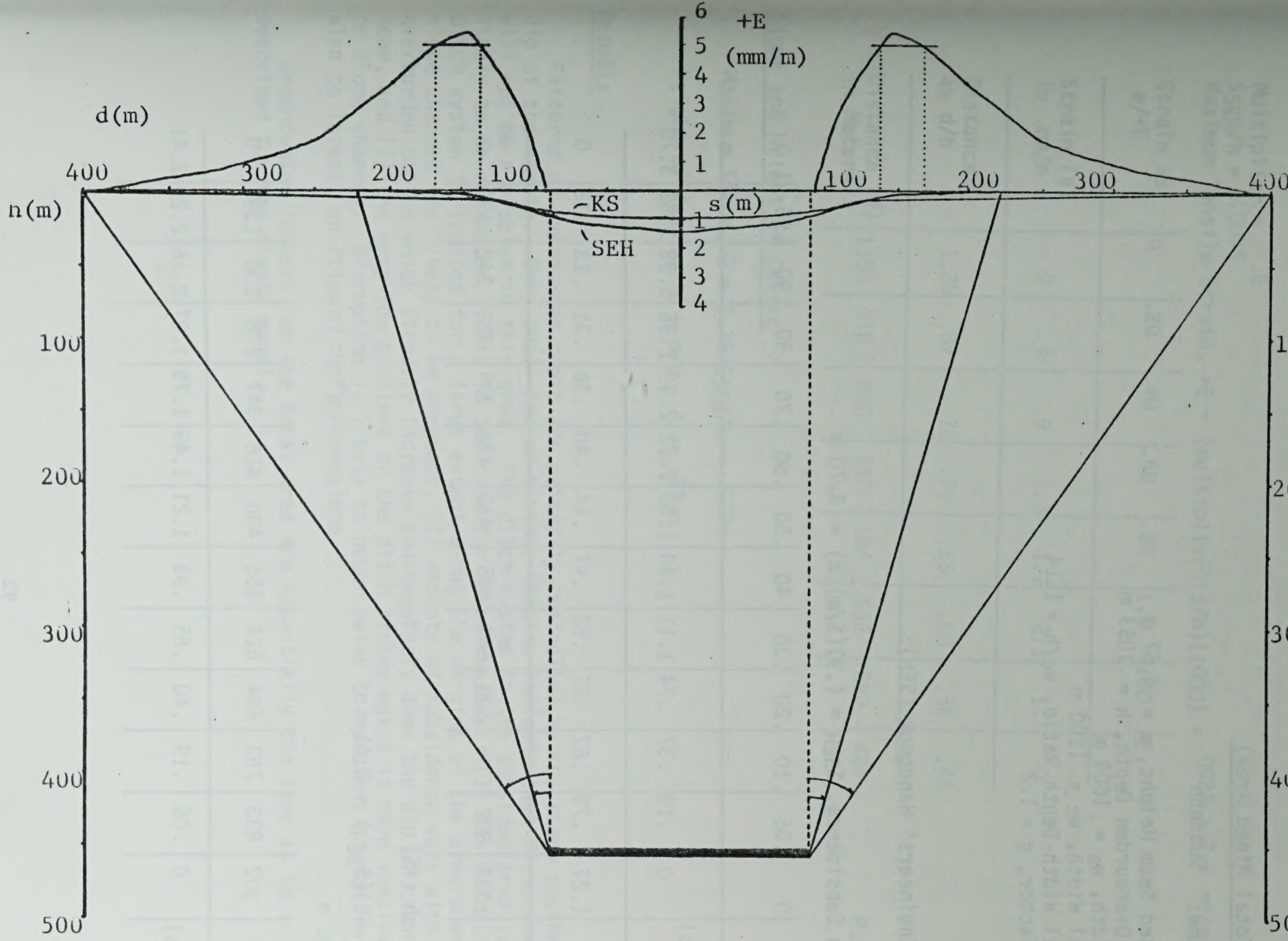


FIGURE 28. - Subsidence and strain profiles over a single mined panel in the North Park Field.

North Park Field

Mine Data (Total Mined Area)

Seam Name: Suddeth

Extracted Seam Height, m = 4.57 m
Median Overburden Depth, h = 1053 m
Area Width, w_a = 1609 m
Critical Width, w_c = 1200 m
Critical Width-Depth Ratio, w_c/h = 1.14
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.70 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.19	.37	.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.52	3.70
Distance as d/h	1.27	.79	.67	.57	.52	.47	.44	.40	.36	.31	.23	.18	0
Distance (d) in Meters	1337	832	706	600	548	495	463	421	379	326	242	190	0

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 2.41 m

D = 902 m

Distance (d) in Meters	902	833	763	694	624	555	486	416	347	278	208	139	0
Subsidence (s) in Meters	0	.05	.19	.40	.65	.93	1.21	1.49	1.75	1.97	2.16	2.29	2.41

Strain

Multiplier = .6
S_{SEH}/h = .0035
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = .0021 = 2.1 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	.4	.9	1.3	1.7	2.1	1.7	0
Distance as d/h	1.29	.87	.76	.70	.65	.60	.56	.46
Distance (d) in Meters	1358	916	800	737	684	632	590	484

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0096

Height of Caving, C = m/g - 1 = 23 m

Results

Patterns of overburden depth are primarily controlled by the steep southwest dip of the strata. Very small median surface strains indicate that fissuring will not be a problem in this area. The ditch system in the subsided area is likely to be disrupted. This is the case for three reasons: (1) the Bostwick Ditch system is located for a large extent along the margins of the area where slope changes are likely to be greatest, (2) amounts of subsidence vary with overburden depths which steadily increase southwesterly down the dip of the seam, and (3) the very low gradient of the ditch system makes it more sensitive to slope changes. Disruption is likely to occur owing to gradient changes and also to lateral shifting of the flow downslope.

Groundwater impacts for the total area are essentially the same as those described for the single panel.

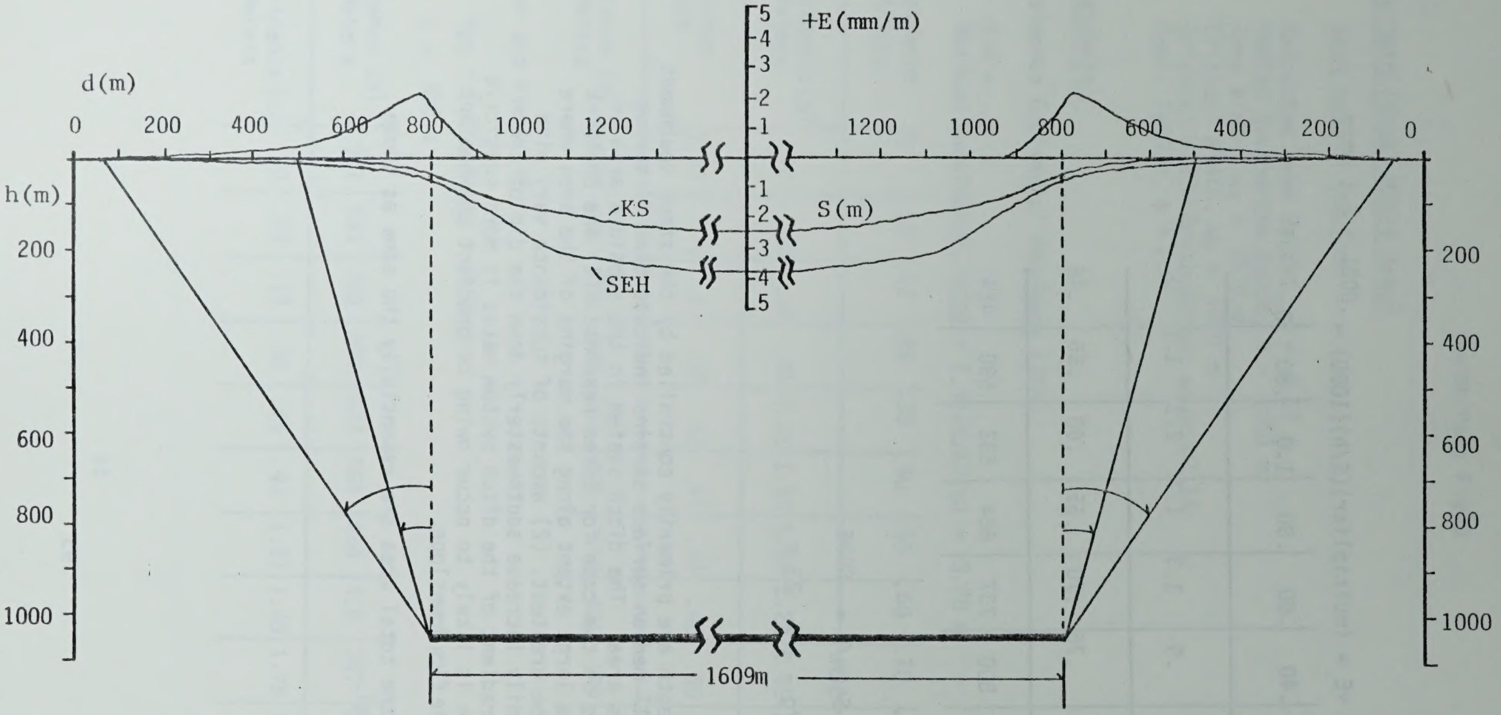
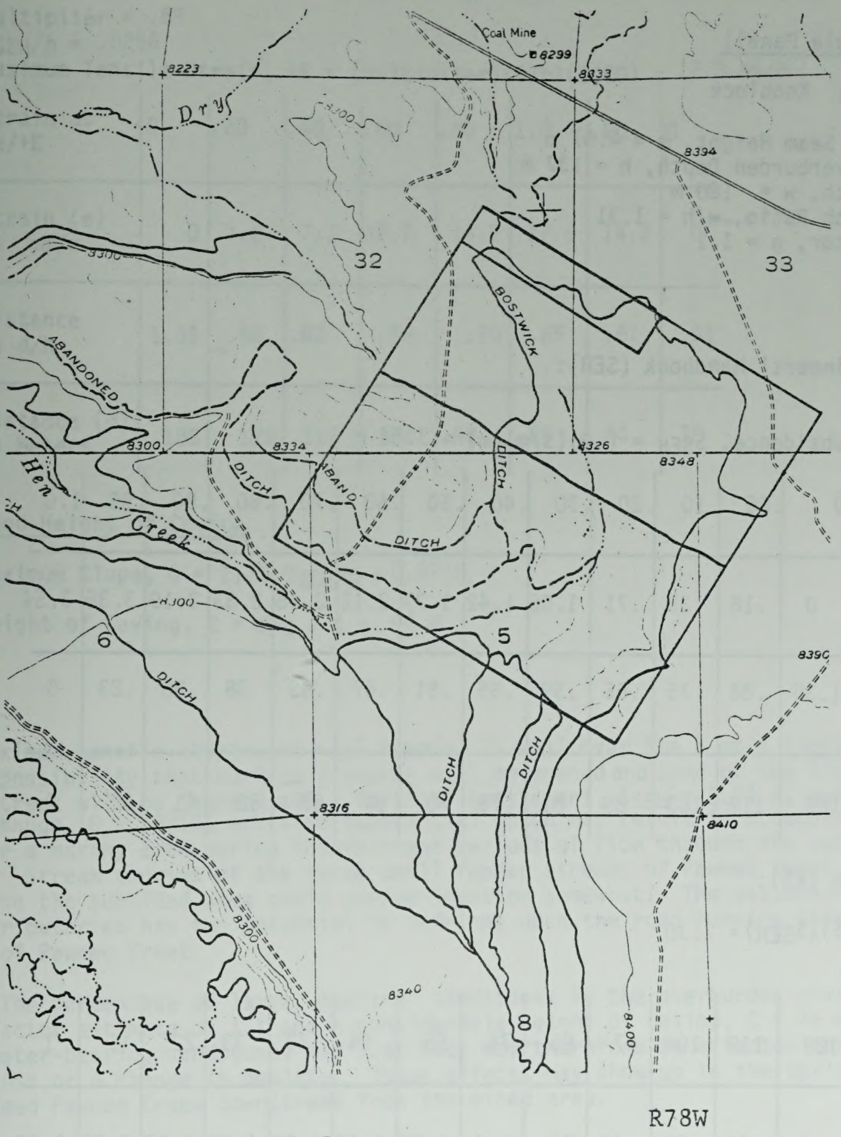


FIGURE 29. - Subsidence and Strain profiles over the total mined area in the North Park Field.



Contour Interval 20 feet

FIGURE 30. - Location of single panel panel and total mined area analyzed in the North Park Field, Colorado. Shaded area indicates depths in excess of median overburden depth.

Birney - Broadus Field

Mine Data (Single Panel)

Seam Name: Knoblock

Extracted Seam Height, m = 4.57 m
Minimum Overburden Depth, h = 137 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 1.31
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .86
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.54 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.18	.35	.71	1.06	1.42	1.77	2.12	2.48	2.83	3.19	3.36	3.54
Distance as d/h	1.35	.86	.75	.65	.59	.55	.51	.47	.43	.38	.30	.23	0
Distance (d) in Meters	185	118	103	89	81	75	70	64	59	52	41	32	0

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 2.30

D = 129 m

Distance (d) in Meters	129	119	108	97	86	76	65	54	43	33	22	11	1
Subsidence (s) in Meters	0	.06	.21	.44	.71	1.0	1.29	1.57	1.81	2.02	2.17	2.27	2.30

Strain

Multiplier = .69
S_{SEH}/h = .0258
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 17.8 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	3.6	7.1	10.7	14.2	17.8	14.2	0
Distance as d/h	1.35	.93	.82	.76	.70	.65	.61	.51
Distance (d) in Meters	185	128	112	104	96	89	84	70

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.0710

Height of Caving, C = m/g - 1 = 46 m

Results

Maximum tensile strain, +E = 17.8 mm/m, is well over the 5 mm/m limit giving a good possibility that surface fissures will be opened and some of the flow in Pawnee Creek will be jeopardized. Vertical settlement, S_{SEH} = 3.54 m, and surface slope change, G = .0710, are also substantial which may result in accumulation of water or a marshy area during intermittent periods of flow through the subsidence trough. Stream courses of the three small feeder streams of Pawnee Creek which tranverse the subsided area could change location somewhat. The eastern-most of these tributaries has the potential to infringe upon the road running through the valley of Pawnee Creek.

The percentage of large, massive sandstones in the overburden gives a swell factor estimate of 1.1 and a considerable height of caving, C = 46 m. Overlying water-bearing sandstones and coal beds may therefore be affected through a water loss or a change in quality. These effects may show up in the springs which feed Pawnee Creek downstream from the mined area.

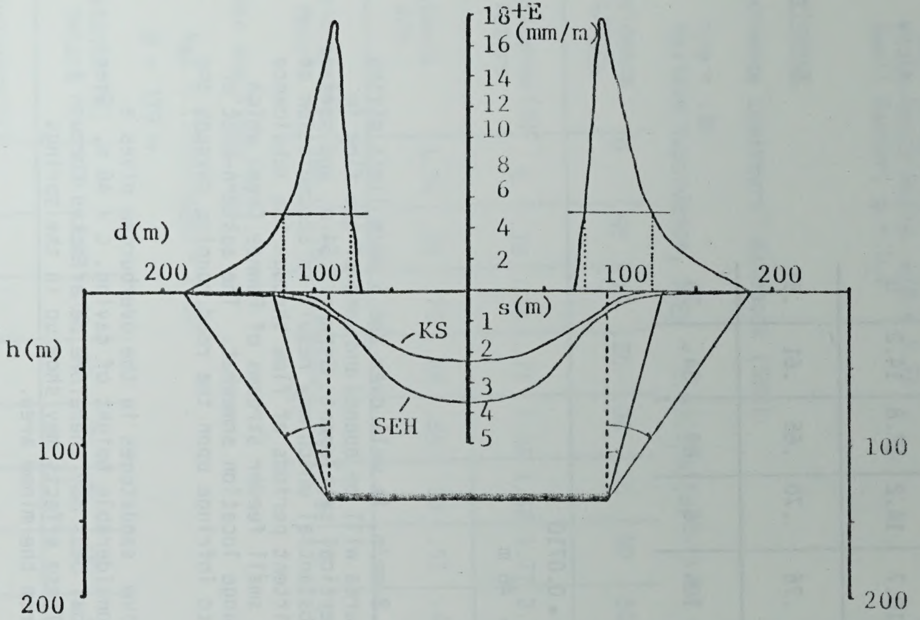


FIGURE 31. - Subsidence and strain profiles over a single mined panel in the Birney-Broadus Field.

Birney-Broadus Field

Mine Data (Total Mined Area)

Seam Name: Knoblock

Extracted Seam Height, m = 4.57 m
Median Overburden Depth, h = 225 m
Area Width, w_a = 1609 m
Critical Width, w_c = 365 m
Critical Width-Depth Ratio, w_c/h = 1.62
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

$S/m = .9$
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 3.70$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.19	.37	.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.52	3.70
Distance as d/h	1.50	1.01	.90	0.80	0.74	0.70	0.66	0.62	0.58	0.53	0.45	0.37	0.05
Distance (d) in Meters	338	227	203	180	167	158	149	140	131	119	101	83	11

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 2.41$ m
$D = 247$ m

Distance (d) in Meters	247	226	206	185	165	144	124	103	82	62	41	21	0
Subsidence (s) in Meters	0	.06	.22	.46	.74	1.05	1.35	1.64	1.90	2.11	2.27	2.37	2.41

Strain

Multiplier = .62
S_{SEH}/h = .0164
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = .0102 = 10.2 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	2.0	4.1	6.1	8.1	10.2	8.1	0
Distance as d/h	1.50	1.08	.97	.91	.85	.80	.76	.66
Distance (d) in Meters	338	243	218	205	191	180	171	149

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0451

Height of Caving, C = m/g - 1 = 46 m

Results

Fissuring resulting from tensile strain should not be a problem in areas of greater than median overburden since the occurence of surface water in these areas is minimal and the amount of strain (10.2 mm/m or less) is relatively small. In areas of less than median overburden dpeths fissuring would most likely be a problem in the southeast corner of the subsided area. Erosion along Pawnee Creek on the northern edge of the area may increase due to vertical settlement and increased channel slope. Sediment production may also be slightly increased from formerly flat plateau surfaces which will experience some in the slope factors of equation 7 along the northwestern and northeastern margins of the area. Deposition will likely occur along Pawnee Creek and its tributaries in the southeast corner of the area where gradients are lower and somewhat reduced by subsidence.

The more widespread effects on the groundwater media associated with the total mined area increases the possibility that the downstream springs on Pawnee Creek will be affected.

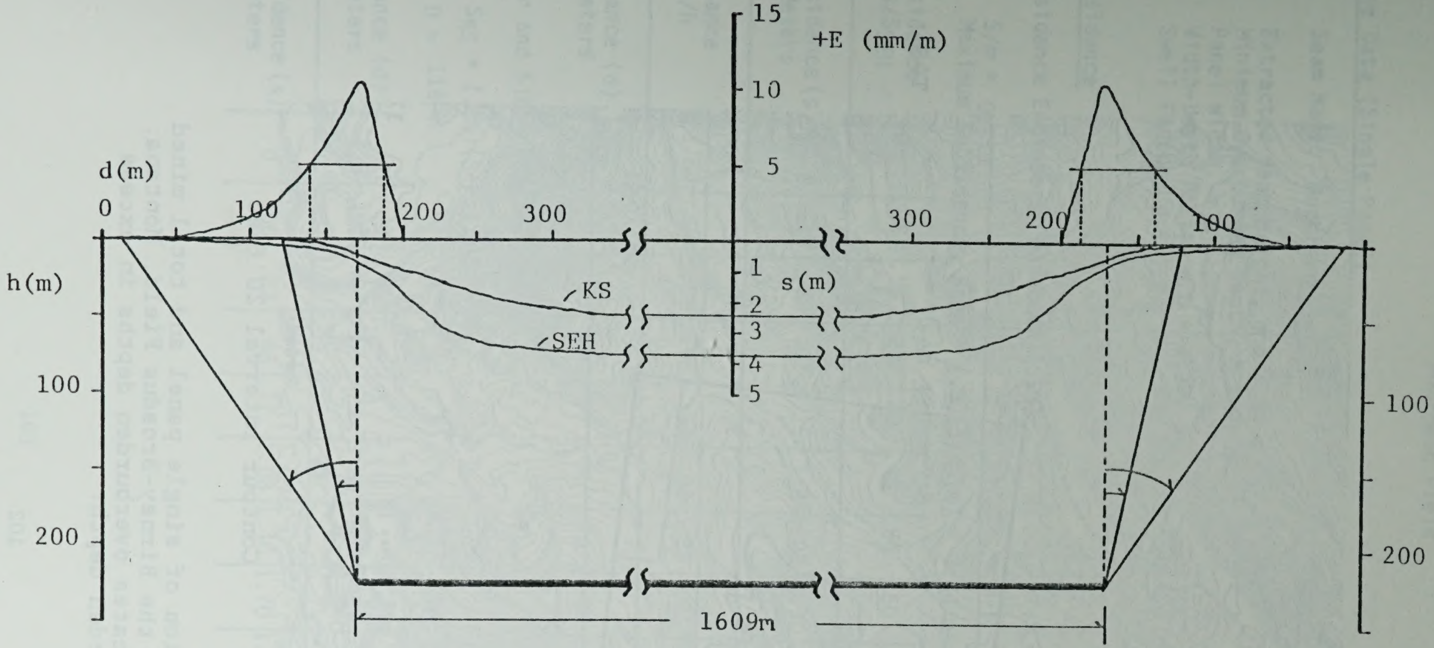


FIGURE 32. - Subsidence and strain profiles over the total mined area in the Birney-Broadus Field.

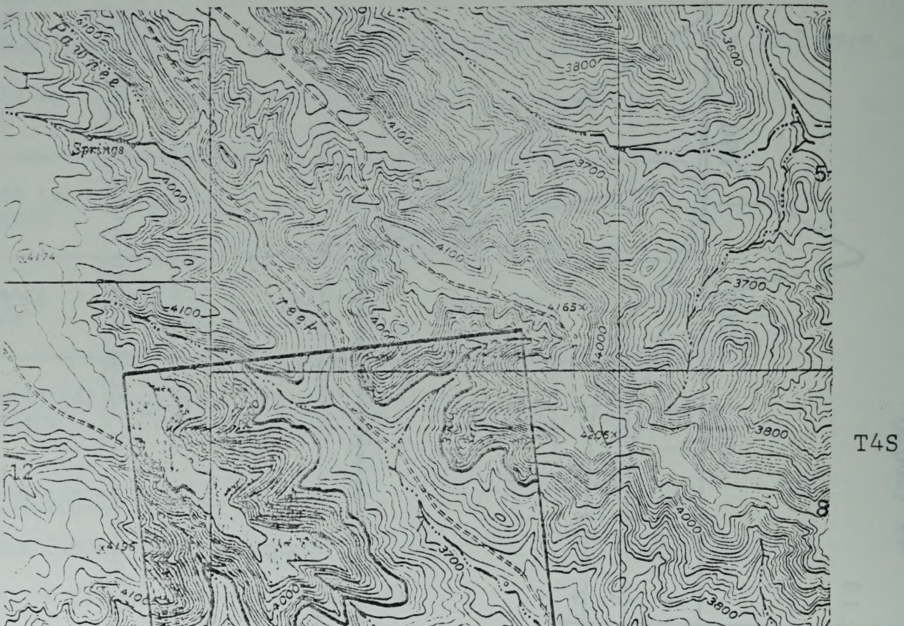


FIGURE 33. - Location of single panel and total mined area analyzed in the Birney-Broadus Field, Montana. Shaded area indicates overburden depths in excess of median overburden depth.

Moorhead Field

Mine Data (Single Panel)

Seam Name: Anderson

Extracted Seam Height, m = 4.88 m
Minimum Overburden Depth, h = 91 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 1.97
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = 0.875
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.84 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.19	..38	.77	1.15	1.54	1.92	2.30	2.69	3.07	3.46	3.65	3.84
Distance as d/h	1.69	1.20	1.08	.98	.93	.89	.85	.81	.77	.72	.64	.56	.15
Distance (d) in Meters	155	110	99	90	85	81	78	74	70	66	59	51	14

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH})$ = 2.50 m

D = 116 m

Distance (d) in Meters	116	107	97	87	78	68	58	49	39	29	20	10	1
Subsidence (s) in Meters	0	.06	.23	.48	.77	1.08	1.40	1.70	1.97	2.19	2.36	2.46	2.50

Strain

Multiplier = .80
S_{SEH}/h = .0420
Maximum Tensile Strain, $+E$ = (multiplier)(S/h)(1000) = 33.6 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	6.7	13.4	20.2	26.9	33.6	26.9	0
Distance as d/h	1.69	1.26	1.15	1.09	1.03	.98	.94	.84
Distance (d) in Meters	155	115	105	100	94	90	86	77

Slope and Height of Caving

Maximum Slope, $G = 2.75\ S_{SEH}/h$ = 0.1155

Height of Caving, $C = m/g - 1$ = 24 m

Results

Most of the thick coal in this field is at shallow depths by the standards of underground mining. For this reason, large tensile strains will be the rule as is the case for this panel where $+E$ = 33.6 mm/m. It is likely that the lake depicted on the map will lose much of its water to open surface fissures as will the intermittent stream flowing through the canyon. Vertical settlement, S_{SEH} = 3.84 m, and slope changes, G = .1155, should also give rise to changes in the lakes' depth and shoreline.

Springs issuing from the Anderson seam downslope where the seam is exposed in outcrops may experience some change in quality due to the exposure of fresh rock surfaces in the caved area of the mine. Impacts should be minimal however, and diminish over time.

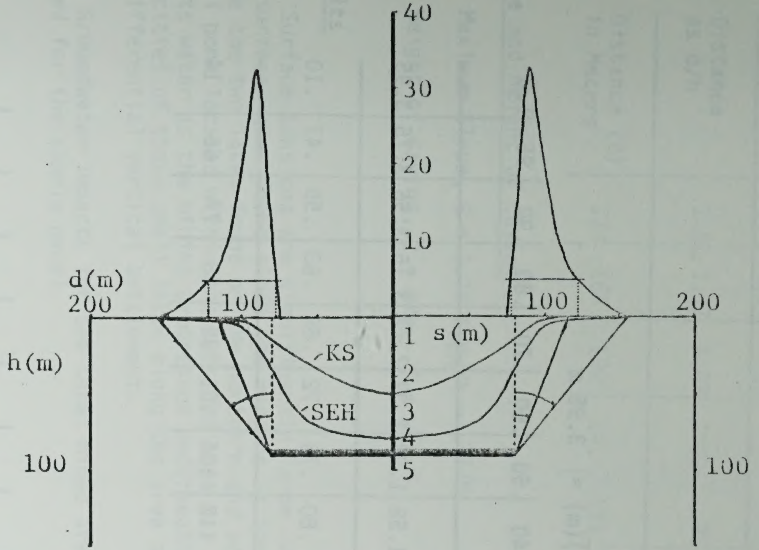


FIGURE 34. - Subsidence and strain profiles over a single mined panel in the Moorhead Field.

Moorhead Field

Mine Data (Total Mined Area)

Seam Name: Anderson

Extracted Seam Height, m = 4.88 m
Median Overburden Depth, h = 140 m
Area Width, w_a = 1609 m
Critical Width, w_c = 250 m
Critical Width-Depth Ratio, w_c/h = 1.79
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.95 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.20	.40	.79	1.19	1.58	1.98	2.37	2.77	3.16	3.56	3.75	3.95
Distance as d/h	1.60	1.11	1.00	.90	.84	.80	.76	.72	.68	.63	.55	.47	.10
Distance (d) in Meters	224	155	140	126	118	112	106	101	95	88	77	66	14

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 2.57

D = 165 m

Distance (d) in Meters	165	151	138	124	110	96	83	69	55	41	28	14	0
Subsidence (s) in Meters	0	.07	.24	.49	.79	1.12	1.44	1.75	2.03	2.26	2.43	2.53	2.57

Strain

Multiplier = .75

S_{SEH}/h = .0282

Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = .0212 = 21.2 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	4.2	8.5	12.7	17.0	21.2	17.0	0
Distance as d/h	1.6	1.17	1.07	1.01	.95	.90	.86	.76
Distance (d) in Meters	224	164	150	141	133	126	120	106

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0776

Height of Caving, C = m/g - 1 = 24 m

Results

Surface tensions are significantly large over the whole area, jeopardizing any surface water found along the margins of the subsided area. This would include the two lakes found on the northern and eastern margins of the area. The small pond located within the subsided area may be damaged or lose a portion of its water as the mining progresses underneath it. The shorelines and holding capacities of those small lakes along the area margins may also be changed due to differential vertical settlement.

Groundwater impacts for the total mined area will be similar to those described for the single panel.

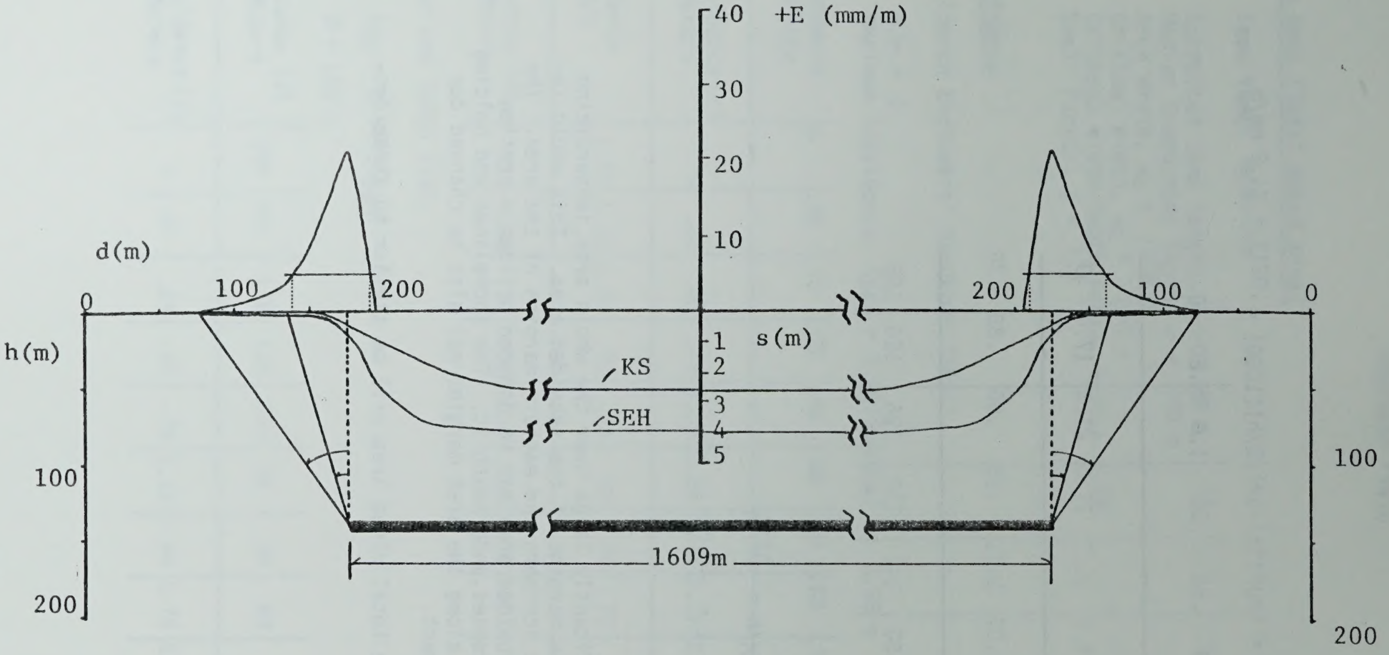


FIGURE 34. - Subsidence and strain profiles over the total mined area in the Moorhead Field.

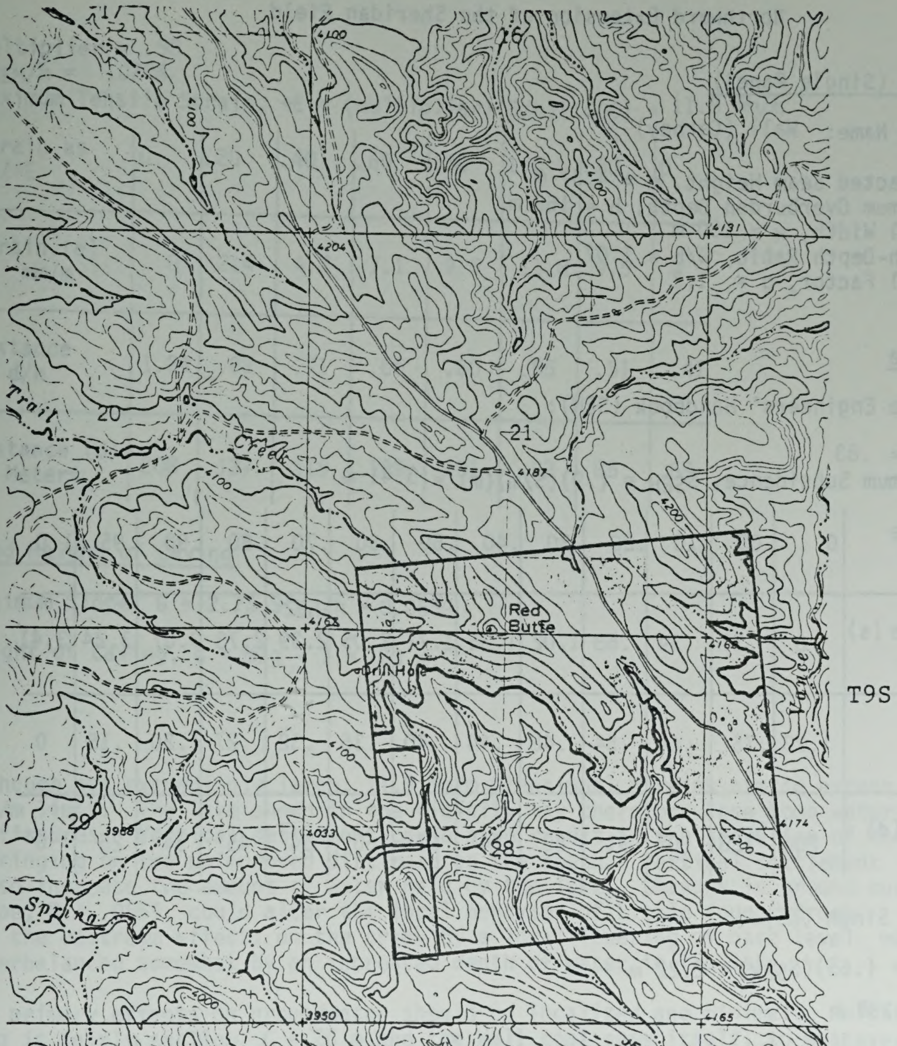


FIGURE 36. - Location of single panel and total mined area analyzed in the Moorhead Field, Montana. Shaded area indicates overburden depths in excess of median overburden depth.

Northward Extension of the Sheridan Field

Mine Data (Single Panel)

Seam Name: Wall (Carney)

Extracted Seam Height, $m = 4.57$ m
Minimum Overburden Depth, $h = 168$ m
Panel Width, $w = 180$ m
Width-Depth Ratio, $w/h = 1.07$
Swell Factor, $g = 1.2$

Subsidence

Subsidence Engineers' Handbook (SEH):

$S/m = .83$
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 3.41$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.17	.34	.68	1.02	1.36	1.71	2.05	2.39	2.73	3.07	3.24	3.41
Distance as d/h	1.23	.75	.64	.54	.48	.44	.40	.36	.32	.27	.20	.15	0
Distance (d) in Meters	206	126	107	91	80	74	67	60	54	45	34	25	0

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 2.22$ m

$D = 138$ m

Distance (d) in Meters	138	127	115	104	92	81	69	58	46	35	23	12	1
Subsidence (s) in Meters	0	.06	.21	.42	.68	.96	1.25	1.51	1.75	1.95	2.09	2.19	2.22

Strain

Multiplier = .58
S_{SEH}/h = .0204
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 11.8 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	2.4	4.7	7.1	9.5	11.8	9.5	0
Distance as d/h	1.24	.82	.71	.65	.60	.55	.51	.41
Distance (d) in Meters	208	137	119	109	101	92	85	69

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.0559

Height of Caving, C = m/g - 1 = 23 m

Results

Although not exceedingly large, 11.8 mm/m, tensional strains are in excess of the 5 mm/m limit. The lake shown in the vicinity may therefore lose some water to surface fissures. Vertical settlement could also result in the shoreline of the lake infringing on the unimproved dirt road to the south. Vertical settlement might also increase the amount of water held by the lake. Changes in ground surface slope, G = .0559, could alter the local behavior of Little Youngs Creek. However, the upstream effects on the creek by a local lowering of base level may be counterbalanced somewhat by an increased depth of water in the lake.

The primary effects on groundwater should be localized and minimal. Height of caving is fairly shallow, C = 23 m and the Wall coal seam itself, to whatever extent it serves as an aquifer, would be most affected.

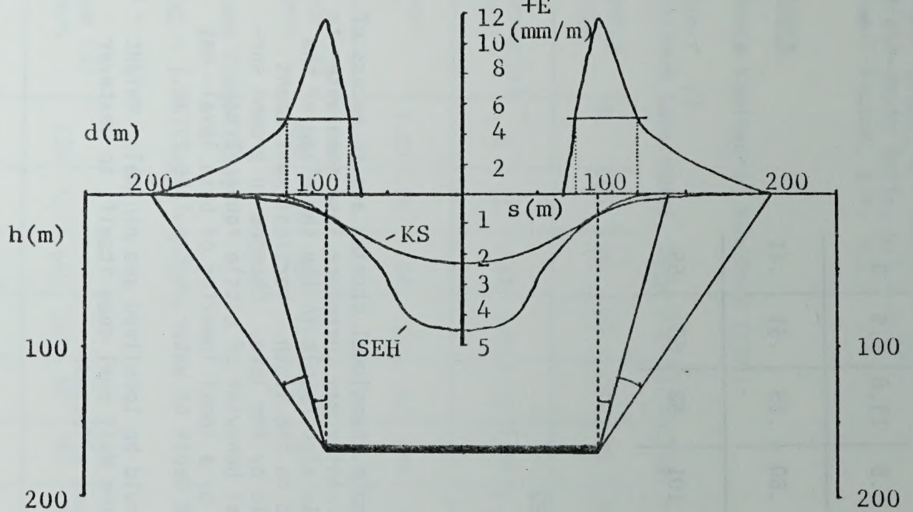


FIGURE 37. - Subsidence and strain profiles over a single mined panel in the Northward Extention of the Sheridan Field.

Northward Extension of the Sheridan Field

Mine Data (Total Mined Area)

Seam Name: Wall (Carney)

Extracted Seam Height, $m = 4.57$ m
Median Overburden Depth, $h = 229$ m
Area Width, $w_a = 1609$ m
Critical Width, $w_c = 375$ m
Critical Width-Depth Ratio, $w_c/h = 1.64$
Swell Factor, $g = 1.2$

Subsidence

Subsidence Engineers' Handbook (SEH):

$S/m = .9$
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 3.70$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.19	.37	.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.52	.370
Distance as d/h	1.52	1.03	.92	.82	.76	.72	.68	.64	.60	.55	.47	.39	.06
Distance (d) in Meters	348	236	211	188	174	165	156	147	137	126	108	89	14

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 2.41$ m

$D = 253$ m

Distance (d) in Meters	253	234	214	195	175	156	136	117	97	78	58	39	0
Subsidence (s) in Meters	0	.05	.19	.40	.65	.93	1.21	1.49	1.75	1.97	2.16	2.29	2.41

Strain

Multiplier = .64
S_{SEH}/h = .0162
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = .0104 = 10.4 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	2.1	4.1	6.2	8.9	10.3	8.3	0
Distance as d/h	1.52	1.10	.99	.93	.87	.82	.78	.68
Distance (d) in Meters	348	252	227	213	199	188	179	156

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0444

Height of Caving, C = m/g - 1 = 23 m

Results

The possibilities for fissuring are moderate with the greatest threat being in the northeast corner of the subsided area. Increased erosion may occur where stream channel (Little Youngs Creek and tributaries) cross into the area. Deposition may result where the stream enters the lake in the northeast corner of the area. Vertical settlement within the subsided area may change the shoreline and storage capacity of the lake.

Impacts on groundwater will probably be confined primarily to the Wall coal seam aquifer.

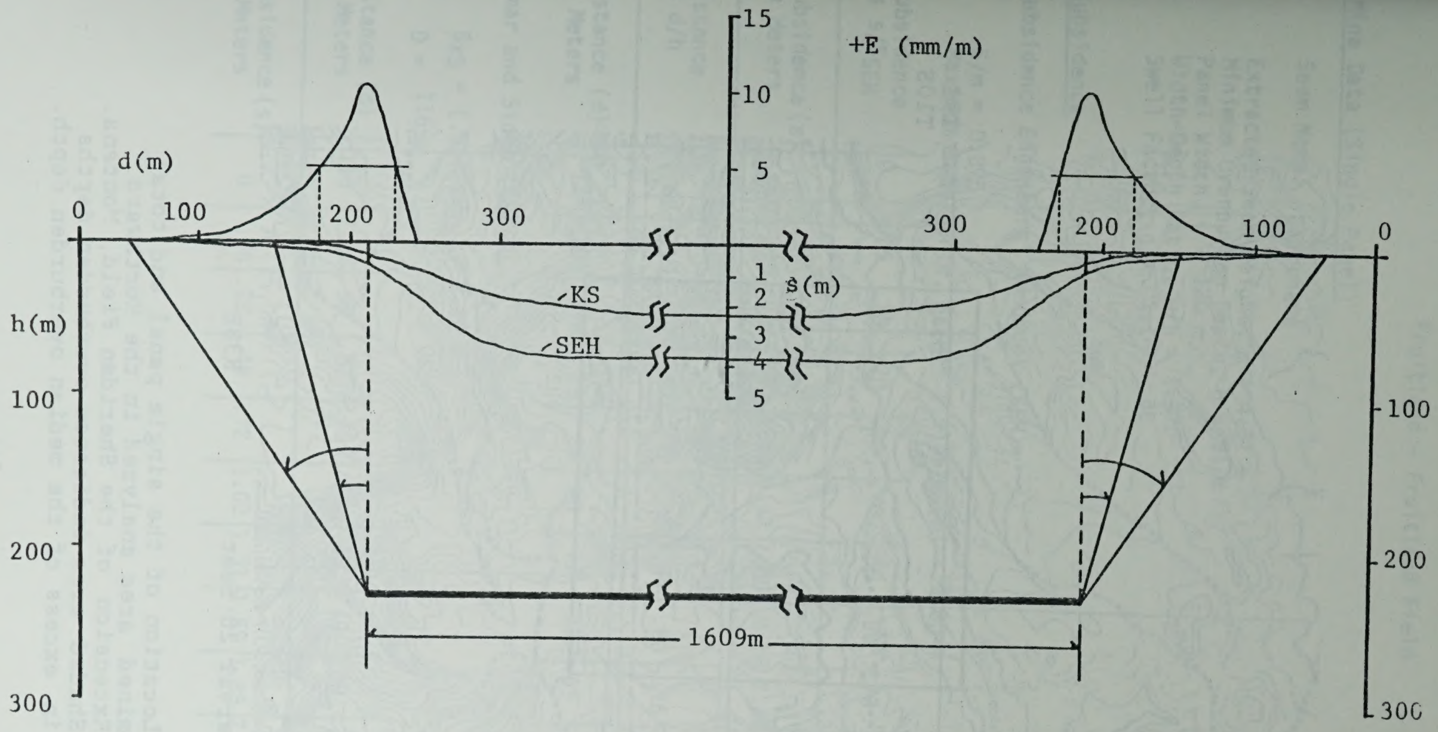


FIGURE 38. - Subsidence and strain profiles over the total mined area in the Northward Extension of the Sheridan Field.

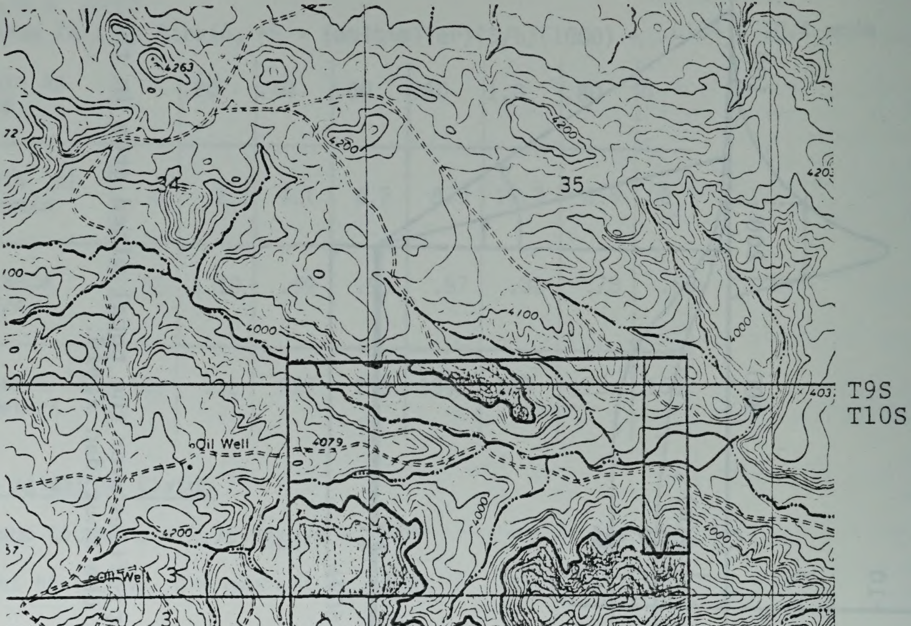


FIGURE 39. - Location of the single panel and total mined area analyzed in the Northward Extension of the Sheridan Field, Montana. Shaded area indicates overburden depths in excess of the median overburden depth.

Fruitland - Fruitland Field

Mine Data (Single Panel)

Seam Name: Carbonero

Extracted Seam Height, m = 4.57 m
Minimum Overburden Depth, h = 91 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 1.97
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

$S/m = 0.875$
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 3.60$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.18	.36	.72	1.08	1.44	1.80	2.16	2.52	2.88	3.24	3.42	3.60
Distance as d/h	1.68	1.19	1.07	.97	.92	.88	.84	.80	.76	.71	.63	.55	.15
Distance (d) in Meters	154	109	98	89	84	80	77	73	69	65	58	50	14

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 2.34$ m
D = 116 m

Distance (d) in Meters	116	107	97	87	78	68	58	49	39	29	20	10	1
Subsidence (s) in Meters	0	.06	.22	.45	.72	1.02	1.31	1.59	1.85	2.05	2.21	2.31	2.34

Strain

Multiplier = .80
S_{SEH}/h = .0394
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 31.5 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	6.3	12.6	18.9	25.2	31.5	25.2	0
Distance as d/h	1.69	1.26	1.15	1.09	1.03	.98	.94	.84
Distance (d) in Meters	155	115	105	100	94	90	86	77

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.1083

Height of Caving, C = m/g - 1 = 46 m

Results

The relatively high subsidence to overburden ratio, S/h = .0394, of this mine creates large tensile strains, +E = 31.5 mm/m far in excess of the 5 mm/m limit. The intermittent Young's Lake and surrounding water courses are therefore subject to drainage into the subsurface through open fissures. The location of the shoreline of Young's Lake may also be changed due to vertical settlement and fairly large changes in slope, G = .1083, along the edges of the trough.

A low swell factor, g = 1.1, owing to hard sandstones in the overburden, gives rise to a height of caving of half the overburden thickness. Local water-bearing sandstone and coal members of the Fruitland formation therefore have a good likelyhood of being altered. These effects however, should be quite localized and minimal since no important regional aquifers are involved.

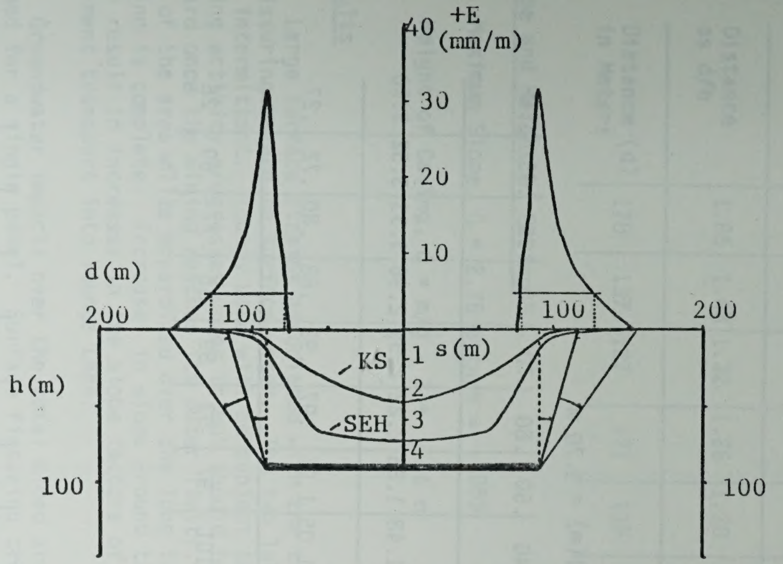


FIGURE 40. - Subsidence and strain profiles over a single mined panel in the Fruitland-Fruitland Field.

Fruitland-Fruitland Field

Mine Data (Total Mined Area)

Seam Name: Carbonero

Extracted Seam Height, m = 4.57 m
Median Overburden Depth, h = 96 m
Area Width, w_a = 1609 m
Critical Width, w_c = 220 m
Critical Width-Depth Ratio, w_c/h = 2.29
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.70 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.19	.37	.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.52	3.70
Distance as d/h	1.85	1.36	1.24	1.14	1.09	1.05	1.01	.97	.93	.88	.80	.72	.27
Distance (d) in Meters	178	131	119	109	105	101	97	93	89	85	77	69	26

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 2.41 m

D = 138 m

Distance (d) in Meters	138	126	115	103	92	80	69	57	46	34	23	11	0
Subsidence (s) in Meters	0	.06	.22	.46	.74	1.05	1.35	1.64	1.90	2.11	2.27	2.37	2.41

Strain

Multiplier = .8
S_{SEH}/h = .0385
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) =.0308 = 30.8 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	6.16	12.3	18.5	24.6	30.8	24.6	0
Distance as d/h	1.85	1.43	1.32	1.26	1.20	1.15	1.11	1.01
Distance (d) in Meters	178	137	127	121	115	110	107	97

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .1059

Height of Caving, C = m/g - 1 = 46 m

Results

Large surface strains associated with the total mined area will present a fissuring hazard to surface water. The two lakes located within the area are intermittent. Youngs Lake will be subject to fissuring effects as the mining activity progresses under it but should be relatively free from that hazard once the mining reaches its outer limits. The lake on the western margin of the area will be jeopardized over the long term by open fissures after mining is complete. Increases in slope around the margin of the subsided area will result in increases in the slope factors of equations and thereby increases in sediment transport into Youngs Lake.

Groundwater impacts over the total mined area are similar to those described for a single panel. Surface fissuring creates the possibility for increased groundwater recharge down to the depth of the fissures.

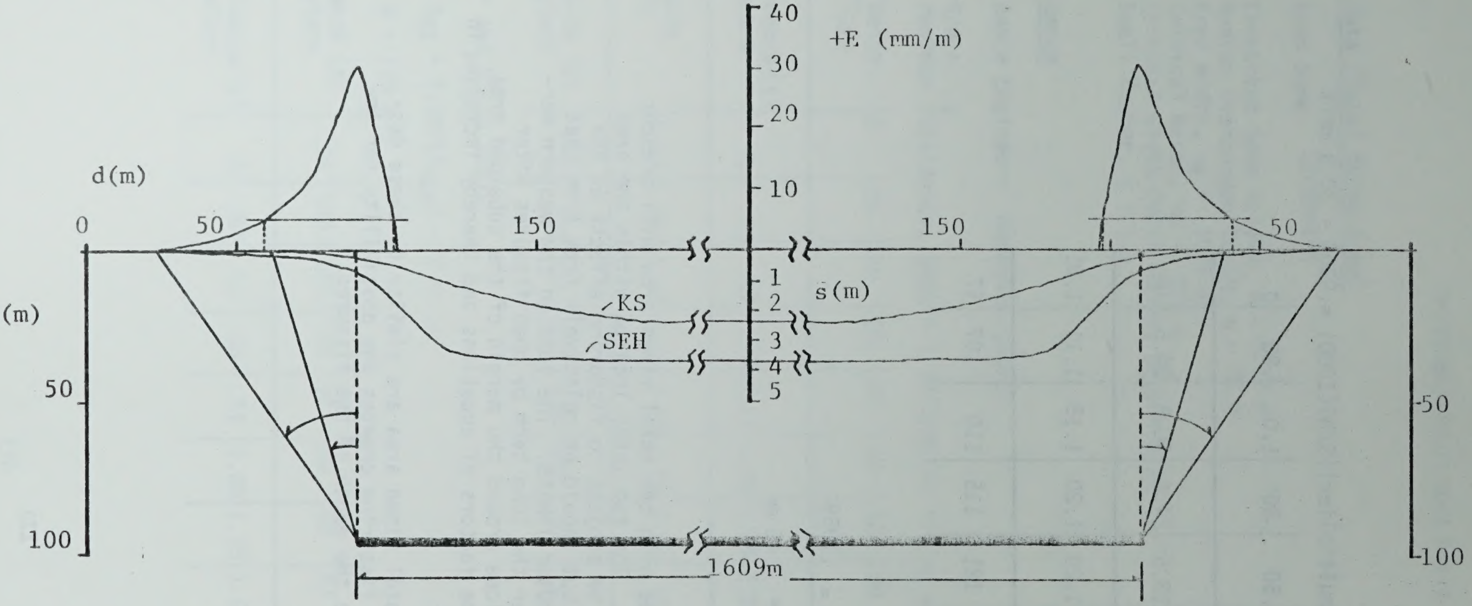


FIGURE 41. - Subsidence and strain profiles over the total mined area in the Fruitland-Fruitland Field.

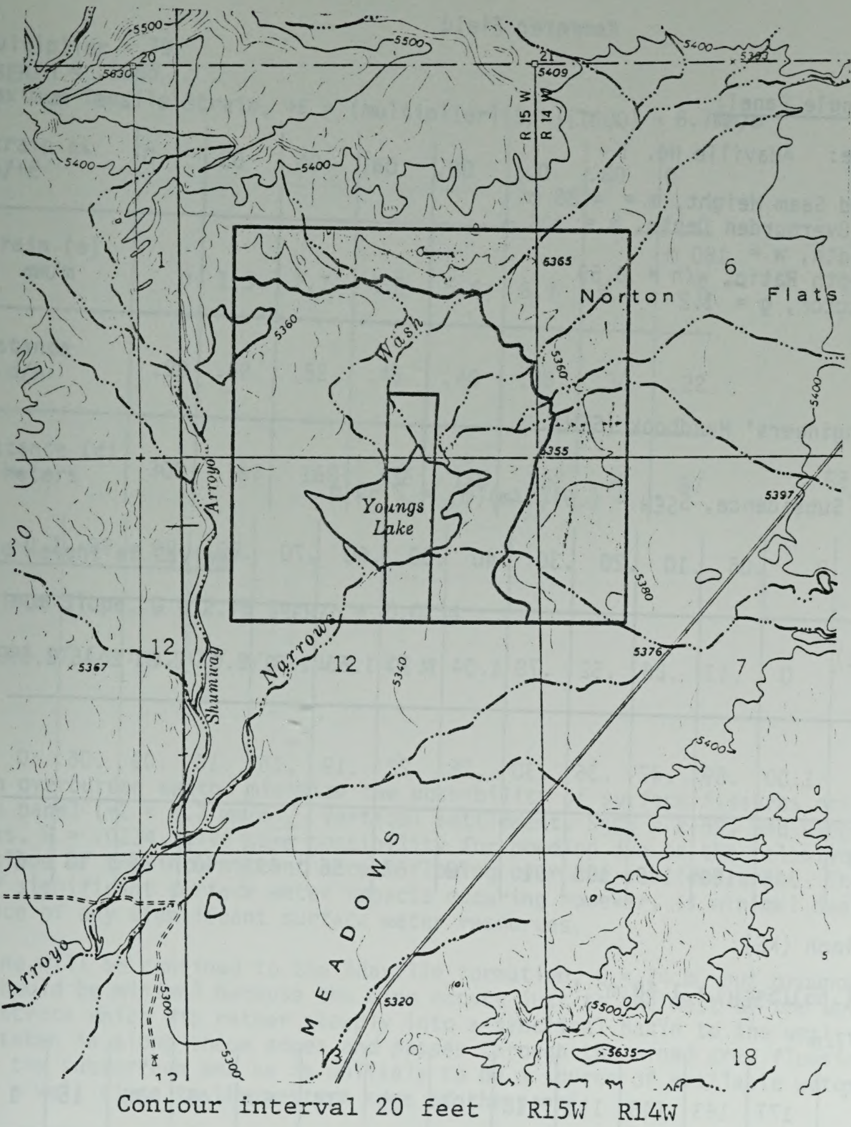


FIGURE 42. - Location of single panel and total mined area analyzed in the Fruitland-Fruitland Field, New Mexico. Shaded area indicates overburden depths in excess of median overburden depth.

Kemmerer Field

Mine Data (Single Panel)

Seam Name: Adaville No. 1

Extracted Seam Height, m = 4.88 m
Minimum Overburden Depth, h = 305 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 0.59
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

$S/m = 0.59$
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 2.59$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.13	.26	.52	.78	1.04	1.30	1.55	1.81	2.07	2.33	2.46	2.59
Distance as d/h	1.00	.59	.47	.36	.30	.26	.22	.19	.16	.13	.09	.06	0
Distance (d) in Meters	303	180	143	108	91	78	67	56	49	40	27	18	6

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 1.68$ m

D = 177 m

Distance (d) in Meters	177	163	148	133	118	104	89	74	59	45	30	15	1
Subsidence (s) in Meters	0	.04	.16	.32	.53	.73	.94	1.15	1.33	1.48	1.59	1.66	1.68

Strain

Multiplier = .79
$S_{SEH}/h = .0085$
Maximum Tensile Strain, $+E = (\text{multiplier})(S/h)(1000) = 6.7\text{mm/m}$

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	1.3	2.7	4.0	5.4	6.7	5.4	0
Distance as d/h	.99	.62	.52	.45	.40	.36	.30	.22
Distance (d) in Meters	300	189	168	136	120	102	90	67

Slope and Height of Caving

Maximum Slope, $G = 2.75\ S_{SEH}/h = 0.0234$

Height of Caving, $C = m/g - 1 = 24$ m

Results

High overburden depths minimize the possibility of surface fissures occuring over this panel (+E = 6.7 mm/m). Vertical settlement, $S_{SEH} = 2.59$, and slope alternations, G = .0234, give some possibility for ponding due to the relatively shallow slope of the intermittent stream flowing over the subsided area. The likelyhood of significant surface water impacts occuring however, is minimal due to the absence of any significant surface water resources.

Caving will be confined to the Adaville formation, C = 24 m, but groundwater impacts should be minimal because the mine occurs just to the west of the upturned edges of strata which dip rather steeply into a synclinal basin to the west. What water is taken in along these edges and passes through the mined area flows to great depths in the subsurface and so is unlikely to be a source of available water unless tapped by a well close to the western edge of the panel.

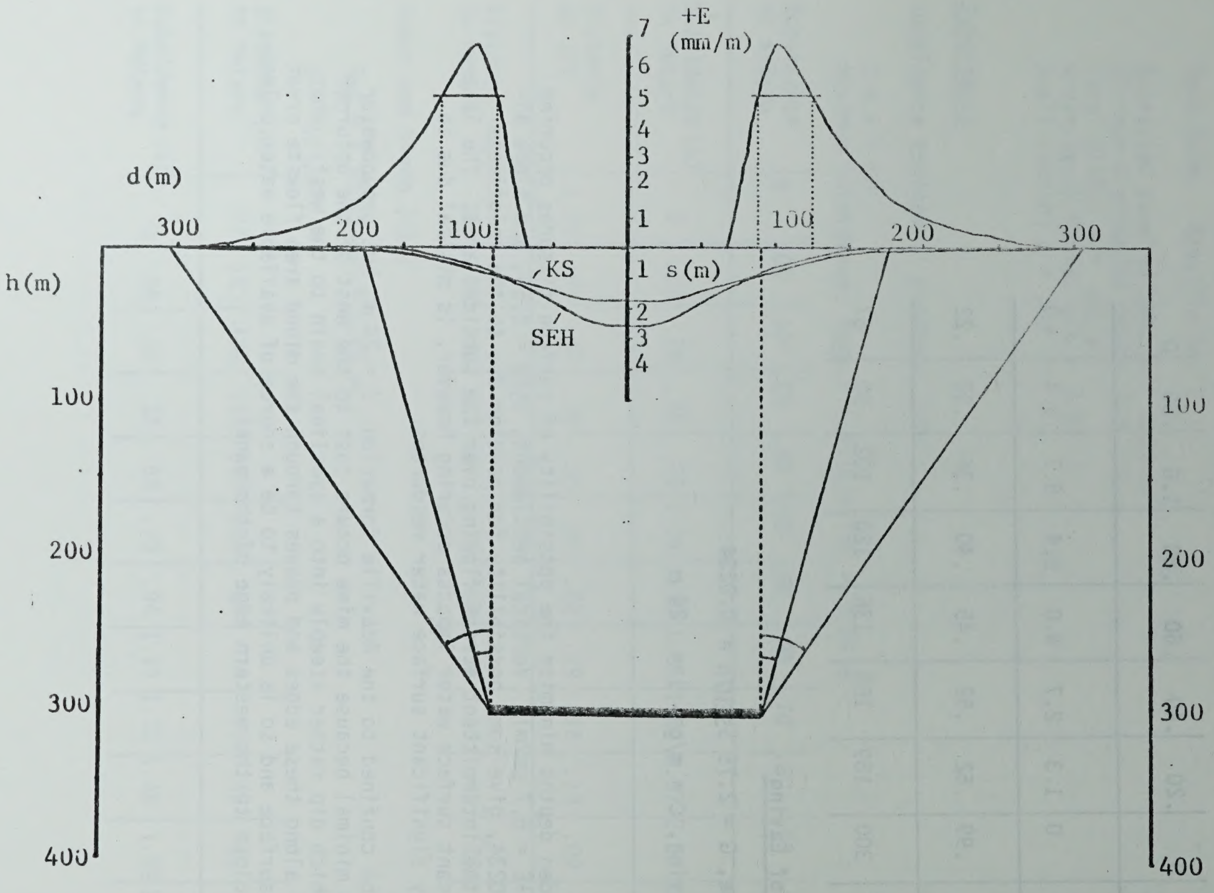


FIGURE 43. - Subsidence and strain profiles over a single mined panel in the Kemmerer Field.

Kemmerer Field

Mine Data (Total Mined Area)

Seam Name: Adaville No. 1

Extracted Seam Height, m = 4.88
Median Overburden Depth, h = 418 m
Area Width, w_a = 1609 m
Critical Width, w_c = 600 m
Critical Width-Depth Ratio, w_c/h = 1.44
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m)$ = 3.95 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.20	.40	.79	1.19	1.58	1.98	2.37	2.77	3.16	3.56	3.75	3.95
Distance as d/h	1.42	.93	.82	.72	.66	.62	.58	.54	.50	.45	.37	.29	.02
Distance (d) in Meters	594	389	343	301	276	259	242	226	209	188	155	121	8

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH})$ = 2.57 m

D = 420 m

Distance (d) in Meters	420	385	350	315	280	245	210	175	140	105	70	35	0
Subsidence (s) in Meters	0	.07	.24	.49	.79	1.12	1.44	1.75	2.03	2.26	2.43	2.53	2.57

Strain

Multiplier = .6
S_{SEH}/h = .0094
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 5.6 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	1.2	2.4	3.6	4.8	5.6	4.8	0
Distance as d/h	1.42	1.00	.89	.83	.77	.72	.68	.58
Distance (d) in Meters	594	418	372	347	322	301	284	242

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0260

Height of Caving, C = m/g - 1 = 24 m

Results

Patterns of overburden depth are primarily determined in this area by the steeply westward dipping nature of the strata. Low tensile strains throughout the mined area are unlikely to result in fissuring. Slope changes may cause increased erosion along the northern edge of the subsided area and some deposition and ponding in the southeast corner of the field. The small holding pond on the northern edge of the field may be disrupted because of its location along the sloping margin of the subsided area. The small intermittent tributaries flowing along the eastern edge of the area could shift laterally down the trough slope toward the interior of the subsided area. The slope factors in equation 7 may be increased along the western edge of the area giving larger overland sediment production.

The discharge of the spring located on the eastern edge of the area may be altered due to its location.

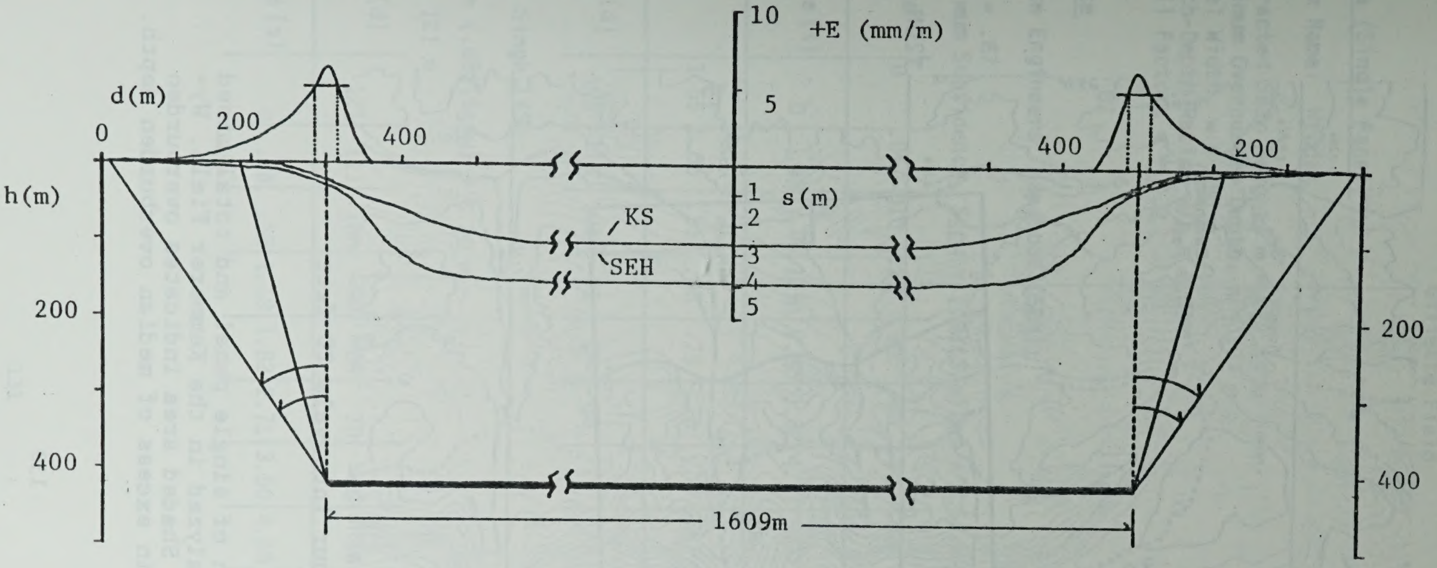


FIGURE 44. - Subsidence and strain profiles for the total mined area in the Kemmerer Field.

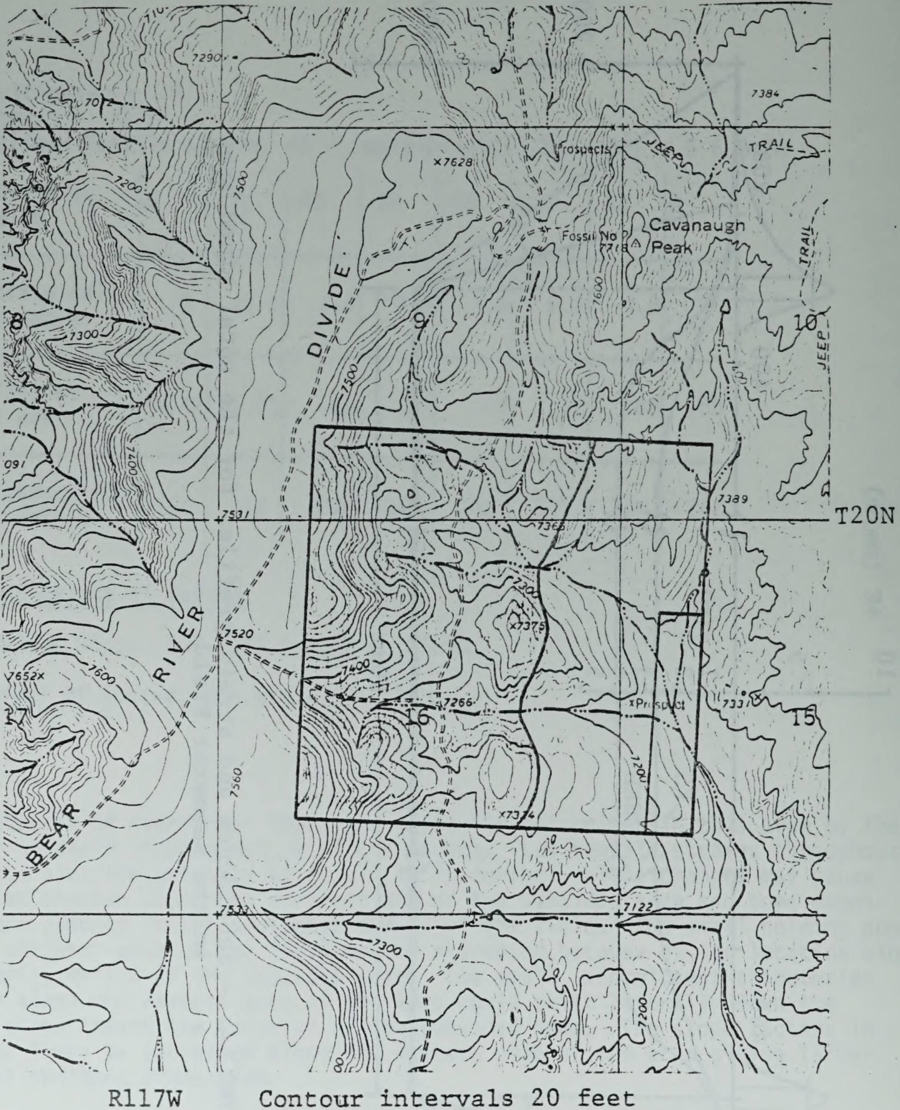


FIGURE 45. - Location of single panel and total mined area analyzed in the Kemmerer Field, Wyoming. Shaded area indicates overburden depths in excess of median overburden depth.

Gillette Field

Mine Data (Single Panel)

Seam Name: Wyodak

Extracted Seam Height, m = 12.19 m
Minimum Overburden Depth, h = 107 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 1.69
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .87
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) = 9.54$ m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.48	.95	1.91	2.86	3.82	4.77	5.72	6.68	7.63	8.59	9.06	9.54
Distance as d/h	1.55	1.06	.95	.85	.79	.75	.71	.67	.63	.58	.50	.42	.08
Distance (d) in Meters	165	113	101	91	84	80	76	71	67	62	53	45	8

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 6.20$ m

D = 121 m

Distance (d) in Meters	121	111	100	90	80	70	60	50	40	30	20	10	1
Subsidence (s) in Meters	0	.16	.58	1.19	1.92	2.71	3.50	4.25	4.92	5.46	5.87	6.12	6.20

Strain

Multiplier = 80
S_{SEH}/h = .0895
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 71.6 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	14.3	28.6	43.0	57.3	71.6	57.3	0
Distance as d/h	1.58	1.15	1.05	.99	.92	.88	.84	.72
Distance (d) in Meters	169	123	112	106	98	94	90	77

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.2459

Height of Caving, C = m/g - 1 = 61 m

Results

The extreme thickness of coal in the Wyodak seam coupled with shallow overburden depths give rise to maximum impacts on whatever water resources may be in close proximity to the mine. Extremely large tensile strains, +E = 71.6 mm/m, are generated over this mine, assuring that fissures would be opened and they would extend for significant depths into the subsurface. If significant surface water resources were present over this mine, large impacts would result. As it is, the intermittent water flowing through the channel above the panel will, in all likelyhood, be diverted into the subsurface. The large amount of vertical settlement, S_{SEH} = 9.54 m, may intercept the groundwater table, giving rise to standing water within the trough. Very large changes in slope, G = .2459, will also affect surface drainage over the affected area.

Caving, C = 61 m, will extend for over half the overburden depth and no doubt intercept many of the overlying water-bearing coal and sandstone layers of the Fort Union formation. Wells tapping these layers on the up-gradient side of the mine may experience losses in flow due to drainage into the caved portion of the mine. Down-gradient wells may experience quality as well as quantity changes owing to flow of groundwater across freshly exposed mineral surfaces.

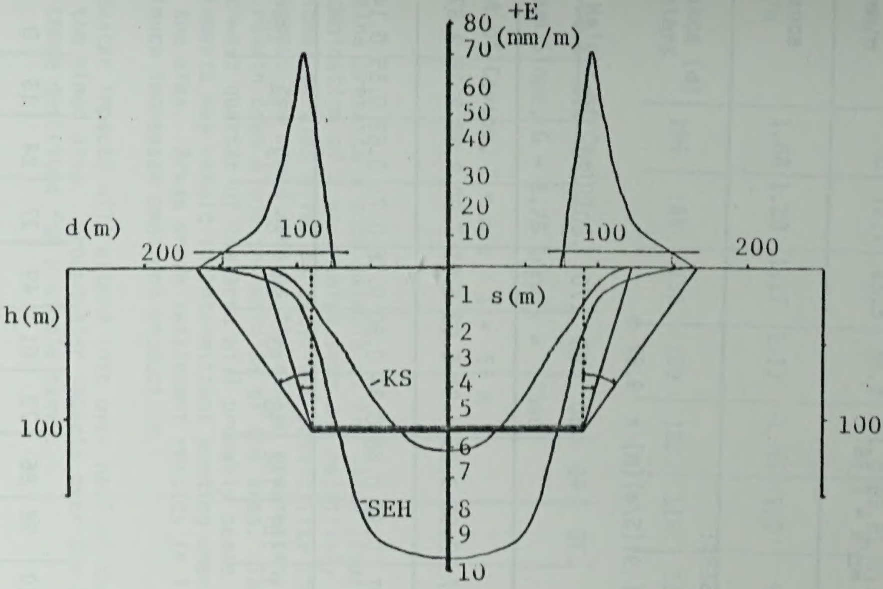


FIGURE 46. - Subsidence and strain profiles over a single mined panel in the Gillette Field.

Gillette Field

Mine Data (Total Mined Area)

Seam Name: Wyodak

Extracted Seam Height, m = 12.19 m
Median Overburden Depth, h = 116 m
Area Width, w_a = 1609 m
Critical Width, w_c = 227 m
Critical Width-Depth Ratio, w_c/h = 1.96
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

$S/m = .9$
Maximum Subsidence, $S_{SEH} = (.9)(S/m)(m) =$ 9.87 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.49	.99	1.97	2.96	3.95	4.94	5.92	6.91	7.90	8.88	9.38	9.87
Distance as d/h	1.68	1.19	1.07	0.97	0.92	0.88	0.84	0.80	0.76	0.71	0.63	0.55	0.14
Distance (d) in Meters	195	138	124	113	107	102	98	93	88	82	73	64	16

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) =$ 6.42 m

$D =$ 147 m

Distance (d) in Meters	147	135	122	110	98	86	73	61	49	37	24	13	0
Subsidence (s) in Meters	0	.16	.6	1.23	1.98	2.79	3.61	4.38	5.07	5.64	6.06	6.32	6.42

Strain

Multiplier = .75
S_{SEH}/h = .0851
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 63.8 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	12.7	25.5	38.3	51.0	63.81	51.0	0
Distance as d/h	1.68	1.28	1.17	1.11	1.05	1.0	.96	.86
Distance (d) in Meters	195	149	136	129	122	116	111	100

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .2340

Height of Caving, C = m/g - 1 = 61 m

Results

This mine presents a good example of the large strata disruptions associated with the combination of a very thick seam and relatively thin overburden. Very large tensional strains give an excellent possibility that fissures will open and close throughout the mined area as the mining progresses. Over the long term, fissures will remain open along the margins of the area. The small intermittent pond in the southwest quarter of the area will probably cease to function. Large vertical settlements may result in intermittent ponding where channels cross the margins of the area. Areas where settlement results in increased slope factors will experience increased sediment production.

Groundwater impacts will extend into over half of the overburden thickness throughout the mined area. Groundwater impacts over the total mined area will be similar to those described for a single panel.

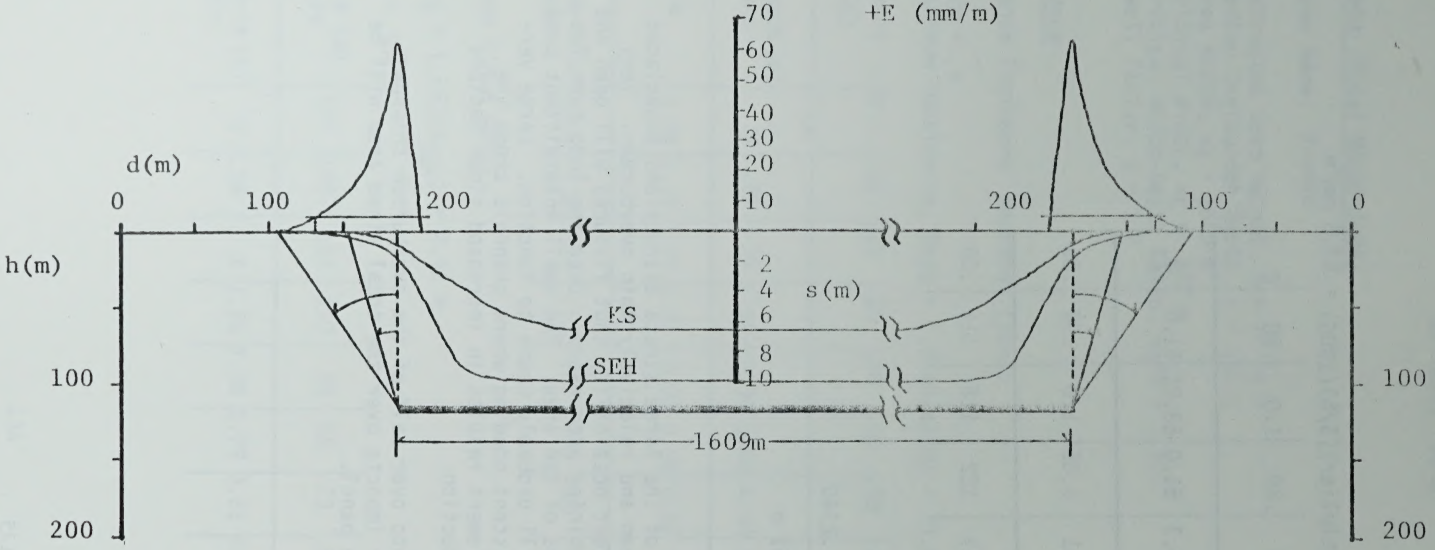
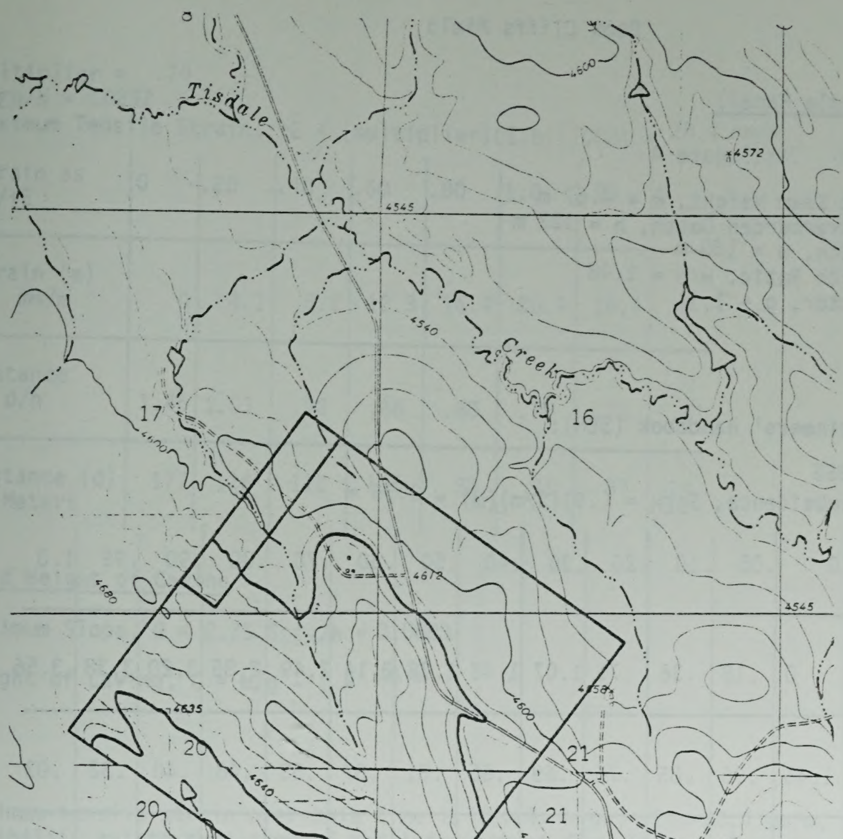


FIGURE 47.- Subsidence and strain profiles over the total mined area in the Gillette Field.



Contour intervals 20 feet

FIGURE 48. - Location of single panel and total mined area analyzed in the Gillette Field, Wyoming. Shaded area indicates overburden depths in excess of the median overburden depth.

Mine Data (Single Panel)

Seam Name: Castlegate A

Extracted Seam Height, m = 4.57 m
Minimum Overburden Depth, h = 122 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 1.48
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = 0.865
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.56 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.18	.36	.71	1.07	1.42	1.78	2.14	2.49	2.85	3.20	3.38	3.56
Distance as d/h	1.45	.96	.85	.75	.69	.65	.61	.57	.53	.48	.40	.32	.03
Distance (d) in Meters	177	117	104	91	84	79	74	69	65	59	49	39	4

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 2.31 m

D = 125 m

Distance (d) in Meters	125	114	103	92	81	70	59	48	37	26	15	4	1
Subsidence (s) in Meters	0	.07	.24	.49	.78	1.09	1.40	1.68	1.93	2.12	2.25	2.31	2.31

Strain

Multiplier = .70
S_{SEH}/h = .0292
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 20.4 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	4.1	8.2	12.3	16.4	20.4	16.4	0
Distance as d/h	1.45	1.03	.92	.86	.80	.75	.71	.61
Distance (d) in Meters	177	126	112	105	98	91	87	74

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.0803

Height of Caving, C = m/g - 1 = 46 m

Results

Maximum tensile strain over this time is fairly high, +E - 20.4 mm/m, so that the possibility exists that some of the intermittent flow through Bear Canyon may be diverted underground through open fissures. Vertical settlement, S_{SEH} = 3.56 m, and slope change, G = .0803, may also give rise to some ponding in the subsided portion of the canyon. Overall surface water effects will be relatively minor since the subsidence is located so high up in the drainage.

Caving, C = 46 m, will not reach above the Blackhawk formation and therefore will not affect the primary water-bearing formations of the area. If local changes in water quality within the Castlegate A seam occur, the downslope effects such as seepage into the Price River should be a minimal part of the total changes induced by extensive mining in the area.

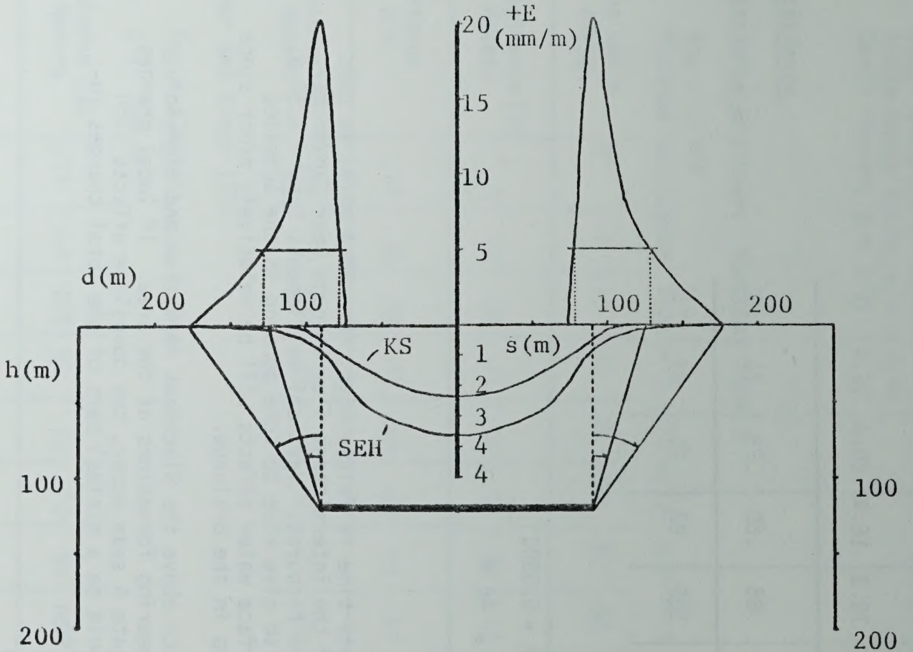


FIGURE 49. - Subsidence and strain profiles over a single mined panel in the Book Cliffs Field.

Book Cliffs Field

Mine Data (Total Mined Area)

Seam Name: Castlegate A

Extracted Seam Height, m = 4.57 m
Median Overburden Depth, h = 335 m
Area Width, w_a = 1609 m
Critical Width, w_c = 560 m
Critical Width-Depth Ratio, w_c/h = 1.67
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.70 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.19	.37	.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.52	3.70
Distance as d/h	1.54	1.05	.94	.84	.78	.74	.70	.66	.62	.58	.49	.41	.07
Distance (d) in Meters	516	352	315	282	261	248	235	221	208	194	164	137	24

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH})$ = 2.41 m

D = 376 m

Distance (d) in Meters	376	345	313	282	251	219	188	157	125	94	63	33	0
Subsidence (s) in Meters	0	.06	.22	.46	.74	1.05	1.35	1.64	1.90	2.11	2.27	2.37	2.41

Strain

Multiplier = .67
S_{SEH}/h = .0110
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = .0074 = 7.4 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	1.5	2.9	4.4	5.9	7.4	5.9	0
Distance as d/h	1.54	1.12	1.01	.95	.89	.84	.80	.70
Distance (d) in Meters	516	375	338	318	298	281	268	234

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0304

Height of Caving, C = m/g - 1 = 46 m

Results

Because of large differences in overburden depths, surface strains show wide variations throughout the mined area. The largest potential for surface fissuring occurs in the vicinity of Bear Canyon in the northeast corner of the area. Elsewhere, impacts on surface water should be limited given the general lack of surface water bodies in the subsided area. Since subsidence tends to be less in areas of thicker overburden, there may be a cumulative increase in slopes from areas of thick overburden toward areas of shallower overburden. The resulting increases in the factor S of equation 7 may give increased sediment production.

Groundwater impacts over the total mined area are not dissimilar from those impacts described for the single mined panel.

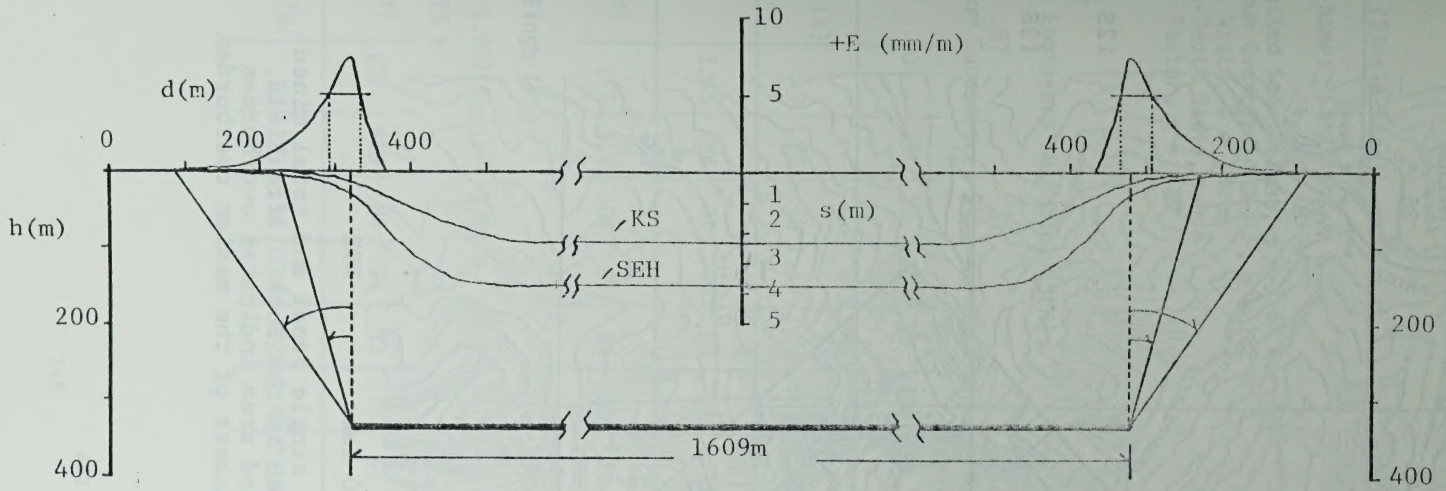
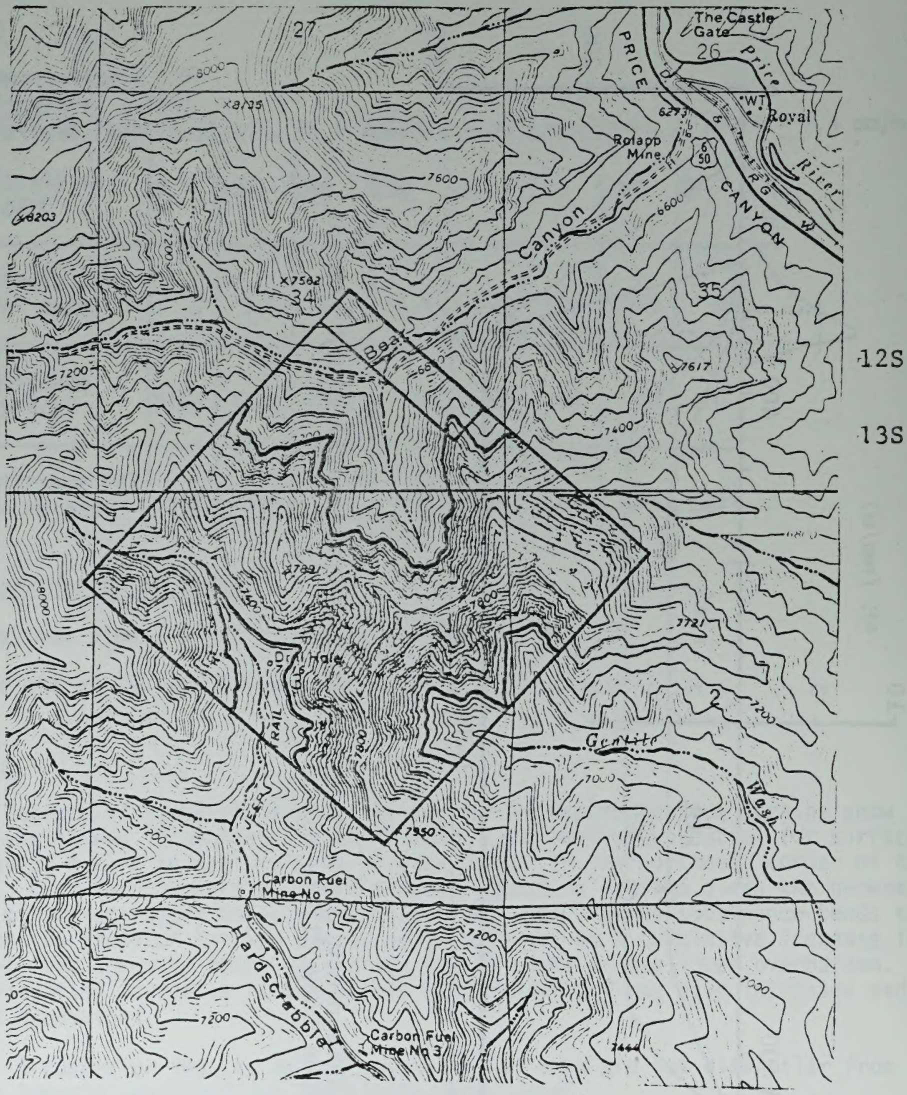


FIGURE 50. - Subsidence and strain profiles over the total mined area of the Book Cliffs Field.



Contour interval 40 feet

FIGURE 51. - Location of single panel and total mined area analyzed in the Book Cliffs Field, Utah. Shaded area indicates overburden depths in excess of the median overburden depth.

Kaiparowits Plateau Field

Mine Data (Single Panel)

Seam Name: Christensen

Extracted Seam Height, m = 7.62 m
Minimum Overburden Depth, h = 122 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 1.48
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .87
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 5.97 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.30	.60	1.19	1.79	2.39	2.99	3.58	4.18	4.78	5.37	5.67	5.97
Distance as d/h	1.45	.96	.85	.75	.69	.65	.61	.57	.53	.48	.40	.32	.03
Distance (d) in Meters	177	117	104	91	84	79	74	69	65	59	49	39	4

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 3.88 m
D = 125 m

Distance (d) in Meters	125	115	104	94	83	73	62	52	42	31	21	10	1
Subsidence (s) in Meters	0	.10	.36	.74	1.20	1.69	2.18	2.65	3.07	3.41	3.67	3.83	3.88

Strain

Multiplier = .75
S_{SEH}/h = .0489
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 36.7 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	7.3	14.7	22.0	29.4	36.7	29.4	0
Distance as d/h	1.45	1.03	.92	.86	.80	.75	.69	.61
Distance (d) in Meters	177	126	112	105	98	91	84	74

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.1347

Height of Caving, C = m/g - 1 = 38 m

Results

A high subsidence to overburden ratio, S/h = .0489, gives rise to extremely high tensile strains, +E = 36.7 mm/m, creating the distinct possibility that the intermittent flow in Horse Spring Canyon will be drained into the subsurface through open fissures. The large amount of vertical settlement, S_{SEH} = 5.97 m, should also give rise to a local depression and the possibility of ponding in Horse Spring Canyon of whatever water escapes the fissures.

Height of caving, C = 38 m, will most likely not extend above the John Henry member of the Straight Cliffs formation. Primary effects will be to the coal seam itself but little is known about its extent or usefulness as an aquifer.

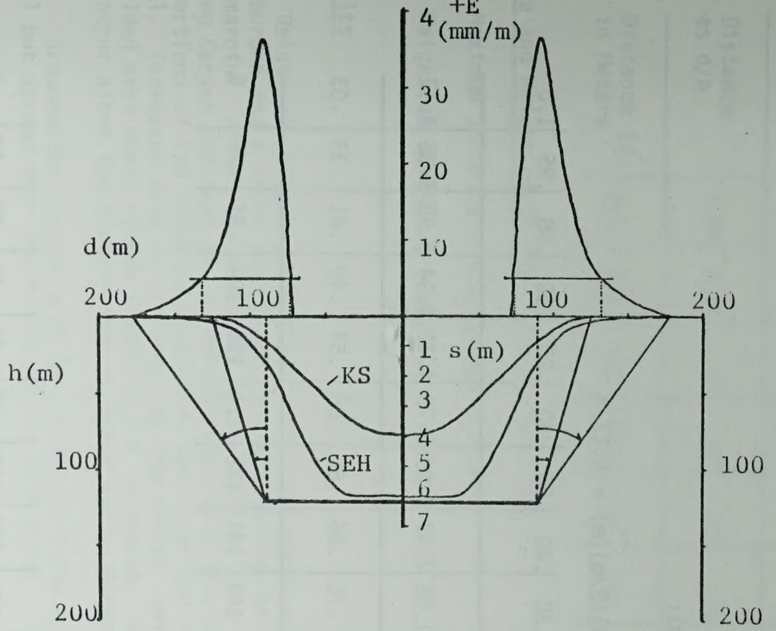


FIGURE 52. - Subsidence and strain profiles over a single mined panel in the Kaiparowits Field.

Kaiparowits

Mine Data (Total Mined Area)

Seam Name: Christensen

Extracted Seam Height, m = 7.62 m
Median Overburden Depth, h = 213 m
Area Width, w_a = 1609 m
Critical Width, w_c = 325 m
Critical Width-Depth Ratio, w_c/h = 1.53
Swell Factor, g = 1.2

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 6.17 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.31	.62	1.23	1.85	2.47	3.09	3.70	4.32	4.94	5.55	5.86	6.17
Distance as d/h	1.46	.97	.86	.76	.70	.66	.62	.58	.54	.49	.41	.33	.03
Distance (d) in Meters	311	207	183	162	149	141	132	124	115	104	87	70	6

Kumar and Singh (KS):

$S_{KS} = (.65)(S_{SEH}) = 4.01$ m

D = 224 m

Distance (d) in Meters	224	205	186	168	149	130	112	93	75	56	37	19	0
Subsidence (s) in Meters	0	.10	.37	.77	1.24	1.75	2.26	2.74	3.17	3.52	3.79	3.95	4.01

Strain

Multiplier = .6
S_{SEH}/h = .0290
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = .0174 = 17.4 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	3.5	7.0	10.4	14.0	17.4	14.0	0
Distance as d/h	1.46	1.04	.93	.87	.81	.76	.72	.62
Distance (d) in Meters	311	222	198	185	173	162	153	132

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0798

Height of Caving, C = m/g - 1 = 38 m

Results

Relatively high tensile strains over the whole mined area due to shallow overburden and a thick seam create the possibility of fissuring around most of the margin above the mined out area. Partial loss of flow through Horse Spring Canyon and part of its tributaries could result. Ponding is unlikely in portions of the subsided area other than over the representative single panel. Increased erosion may occur on the western and southern edges of the subsided area where stream gradients are increased. Corresponding deposition may occur along the eastern edge in Horse Spring Canyon.

Groundwater impacts will be similar to those experienced by the single panel but spread over the entire square mile area.

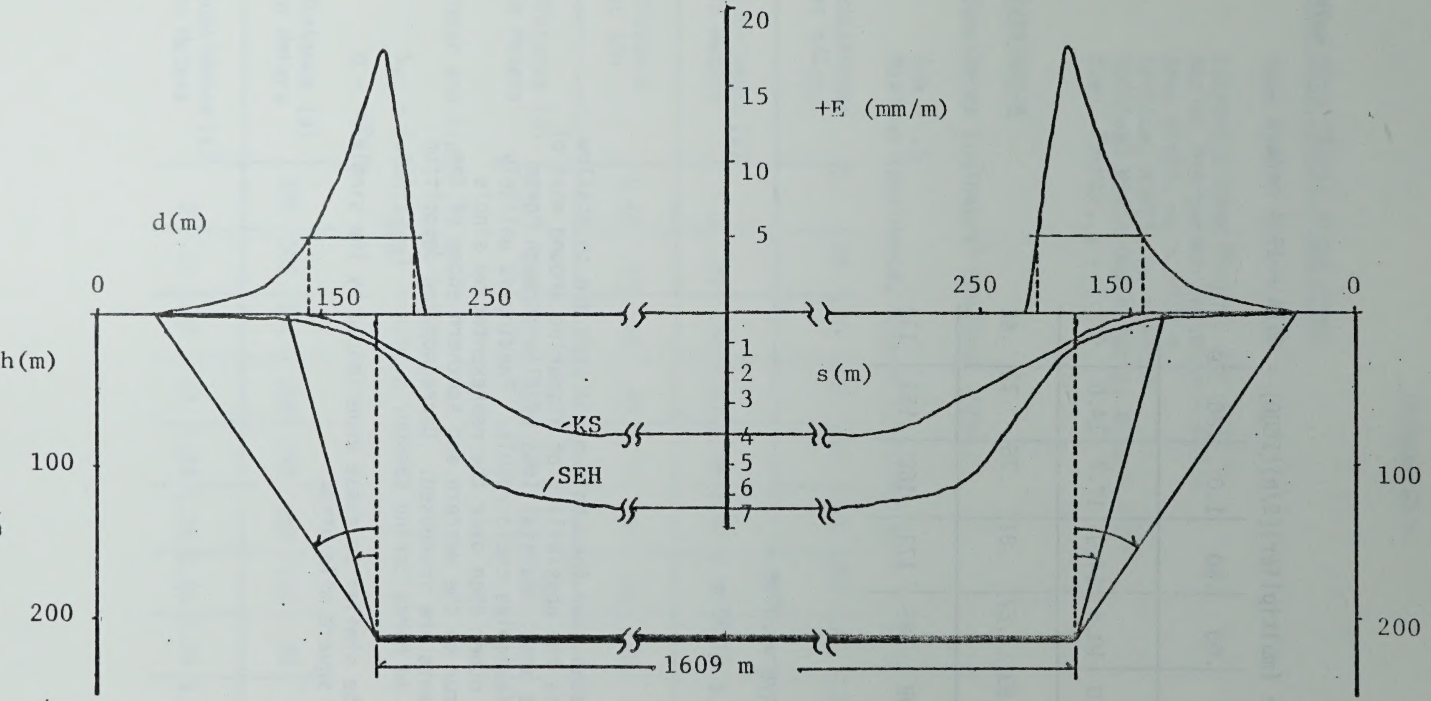
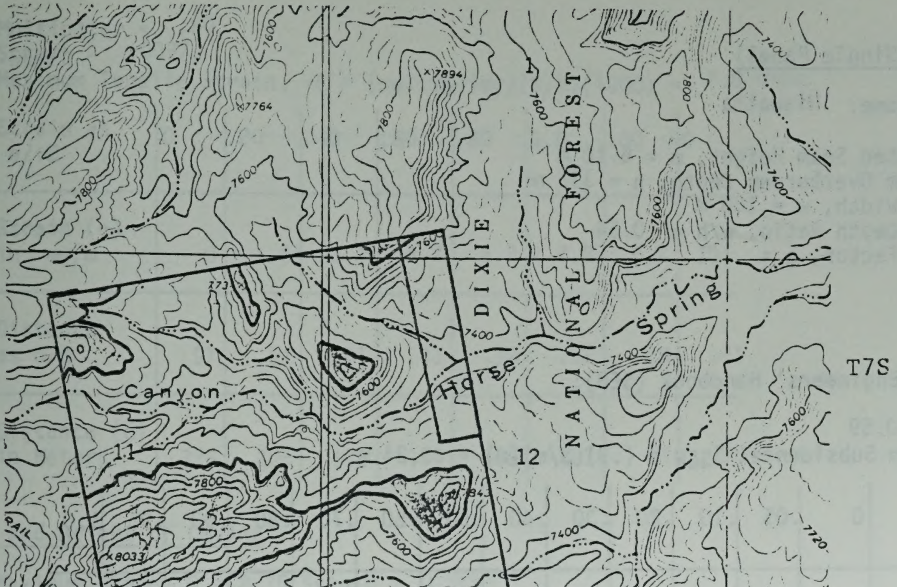


FIGURE 53. - Subsidence and strain profilesover the total mined area for the Kaiparowits Field.



Contour interval 40 feet R1E R2E

FIGURE 54. - Location of single panel and total mined area analyzed in the Kaiparowits Field, Utah. Shaded area indicates overburden depths in excess of median overburden depth.

Wasatch Plateau Field

Mine Data (Single Panel)

Seam Name: Hiawatha

Extracted Seam Height, m = 6.10 m
Minimum Overburden Depth, h = 335 m
Panel Width, w = 180 m
Width-Depth Ratio, w/h = 0.54
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = 0.59
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 3.24 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.16	.32	.65	.97	1.30	1.62	1.94	2.27	2.59	2.92	3.08	3.24
Distance as d/h	.97	.59	.47	.34	.29	.25	.21	.18	.15	.12	.08	.06	0
Distance (d) in Meters	325	198	158	114	97	84	70	60	50	40	27	20	0

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 2.11 m

D = 186 m

Distance (d) in Meters	186	170	154	138	122	106	90	74	58	42	26	10	1
Subsidence (s) in Meters	0	.06	.21	.43	.68	.96	1.23	1.49	1.72	1.90	2.02	2.09	2.11

Strain

Multiplier = .80

S_{SEH}/h = .0097

Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 7.8 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	1.6	3.1	4.7	6.2	7.8	6.2	0
Distance as d/h	.97	.61	.51	.43	.39	.32	.28	.21
Distance (d) in Meters	325	205	171	144	131	107	94	70

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = 0.0266

Height of Caving, C = m/g - 1 = 61 m

Results

The low subsidence to overburden ratio, S/h = .0097, for this mine results in small maximum tensile strain, +E = 7.8 mm/m, and little likelihood of surface fissures opening to drain surface waters from the Left Fork of Cedar Creek. Some change in surface slope, G = .0266, is to be expected but it should have little impact since the panel is located so high up in the drainage and surface slope is fairly steep to start with.

Caving, C = 61 m, will not reach up into the water-bearing Flagstaff limestone, North Horn formation, Price River formation, or the Castlegate sandstone. Possible groundwater effects should therefore be limited to the Blackhawk formation and specifically to the mined Hiawatha seam. Minor water quality effects may be felt downstream through seepage into the Left Fork of Cedar Creek but will likely be overshadowed by the effluents from the Mohrland Mine.

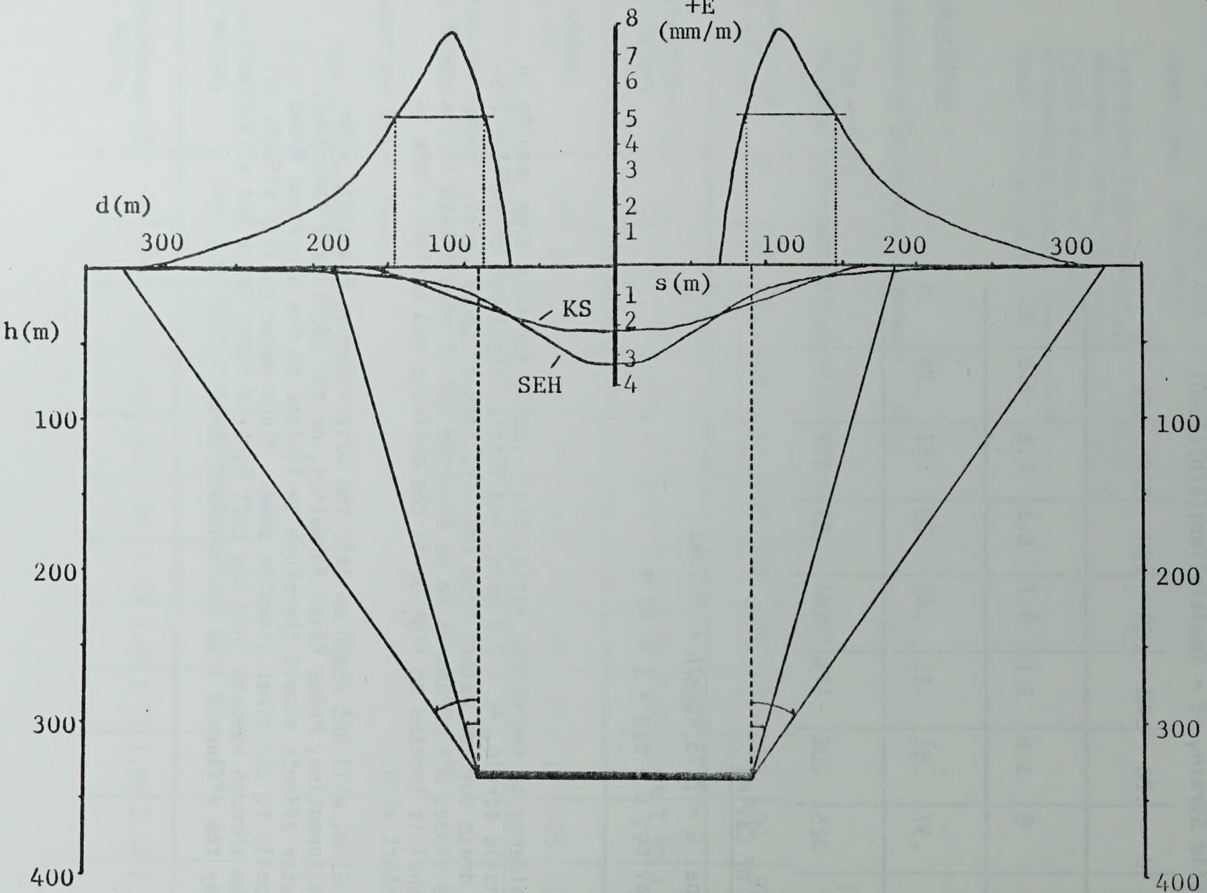


FIGURE 55. - Subsidence and strain profiles over a single mined panel in the Wasatch Field.

Wasatch Plateau Field

Mine Data (Total Mined Area)

Seam Name: Hiawatha

Extracted Seam Height, m = 6.10 m
Median Overburden Depth, h = 347 m
Area Width, w_a = 1609 m
Critical Width, w_c = 580m
Critical Width-Depth Ratio, w_c/h = 1.67
Swell Factor, g = 1.1

Subsidence

Subsidence Engineers' Handbook (SEH):

S/m = .9
Maximum Subsidence, S_{SEH} = (.9)(S/m)(m) = 4.94 m

Subsidence as s/S_{SEH}	0	.05	.10	.20	.30	.40	.50	.60	.70	.80	.90	.95	1.0
Subsidence (s) in Meters	0	.25	.49	.99	1.48	1.98	2.47	2.96	3.46	3.95	4.45	4.69	4.94
Distance as d/h	1.55	1.06	.95	.85	.79	.75	.71	.67	.63	.58	.50	.42	.07
Distance (d) in Meters	538	368	330	295	274	260	246	233	219	201	174	146	24

Kumar and Singh (KS):

S_{KS} = (.65)(S_{SEH}) = 3.21 m

D = 390 m

Distance (d) in Meters	390	357	325	292	260	227	195	162	130	97	65	32	0
Subsidence (s) in Meters	0	.08	.3	.61	.99	1.4	1.81	2.19	2.54	2.82	3.04	3.17	3.21

Strain

Multiplier = .67
S_{SEH}/h = .0142
Maximum Tensile Strain, +E = (multiplier)(S/h)(1000) = 9.5 mm/m

Strain as e/+E	0	.20	.40	.60	.80	1.0	.80	0
Strain (e) in mm/m	0	1.9	3.8	5.7	7.6	9.51	7.6	0
Distance as d/h	1.55	1.11	1.01	.95	.89	.84	.80	.70
Distance (d) in Meters	538	385	351	330	309	292	278	243

Slope and Height of Caving

Maximum Slope, G = 2.75 S_{SEH}/h = .0391

Height of Caving, C = m/g - 1 = 61 m

Results

Surface strain is low over the mined area due to generally high overburden thicknesses. Differential amounts of vertical settlement going from areas of less to areas of more overburden may result in increases to the slope factors in equation 7 and therefore to increased overland sediment production. Ponding may occur at the discharge point of Mud Spring due to significant vertical settlement within the subsided area.

Groundwater impacts over the entire mined area will be similar to those described for the single panel. Changes in gradient within the subsided area may alter the discharge of Mud Spring.

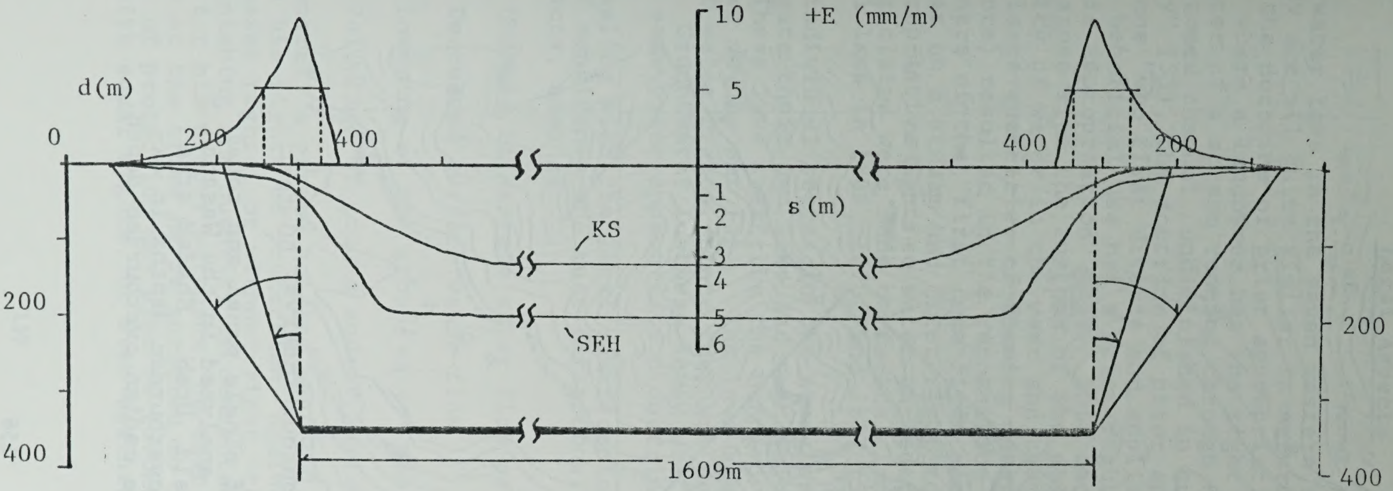


FIGURE 56. - Subsidence and strain profiles overthe total mined area, Wasatch Plateau Field.

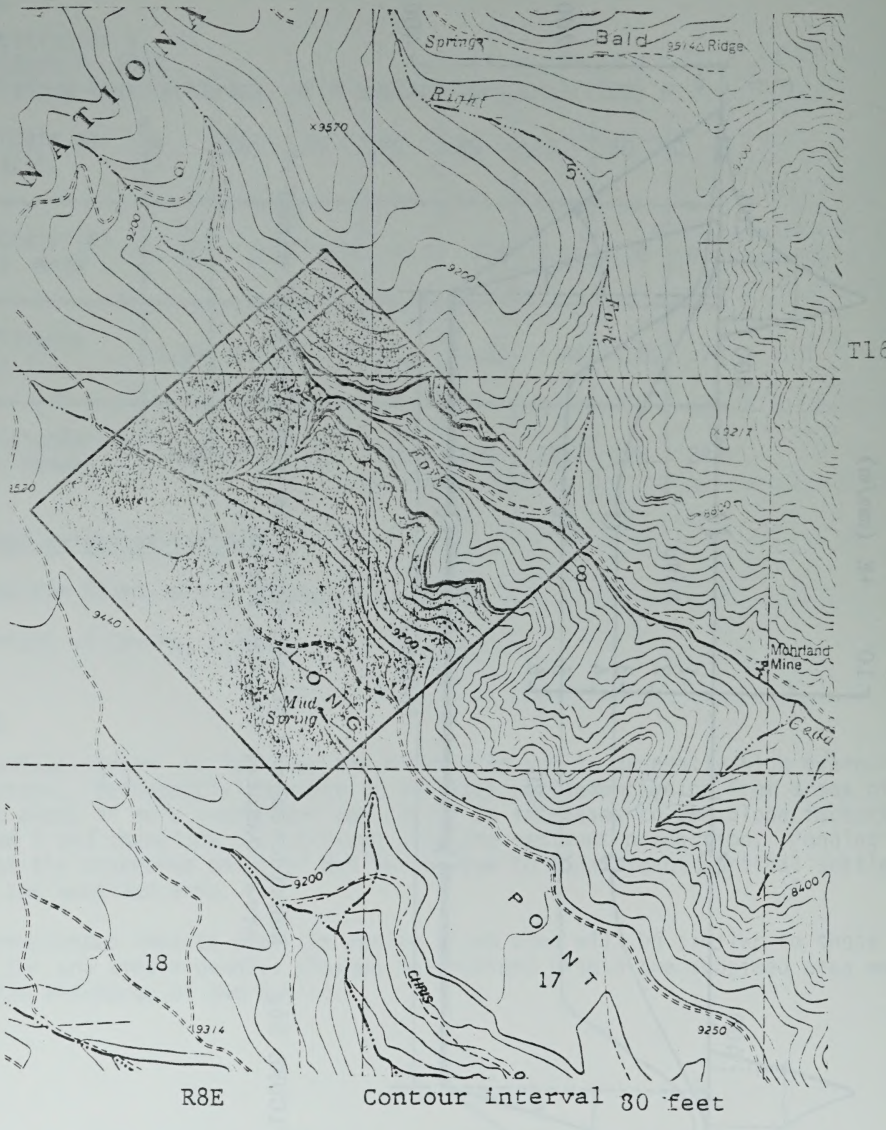


FIGURE 57. - Location of single panel and total mined area analyzed in the Wasatch Plateau Field, Utah. Shaded area indicates overburden depths in excess of the median overburden depth.

Legal Aspects

The water laws in the seven western states considered in this study are all quite similar in nature, as they all are based on the doctrine of prior appropriation. Unlike riparian doctrine, where a landowner has the right to "the natural flow of the water of a stream running through or along his land, in its accustomed channel, undiminished in quantitiy and unimpared in quality" (53), the doctrine of prior appropriation provides that the one "who first diverts and applies the waters of a stream to beneficial use has a prior right thereto, to the extent of his appropriation" (53). This doctrine of prior appropriation arose from the customs of the gold miners in the 1800's. The scarcity of water in the west and the fact that mining gold required large quantities of flowing water (to wash the gold from the ore) resulted in the recognition by the informal court of the miners of the "first come first served" principle. The first miner on a stream had first right to the available water. These appropriative rights to water on federal lands (almost all the mining claims were made on federal land) were recognized by federal laws in 1866, 1870, and 1877 (54).

The individual states in the study area have since gone on to promulgate their own laws and regulations governing appropriations. These laws prescribe the manner, amounts, and uses to which water may be put (55). The laws also provide for the protection of water rights, since they are considered rights of property. Groundwater in these seven states is also treated under the same prior appropriation doctrine.

In dealing with the legal ramifications of the hydrologic impacts of subsidence one must first consider the possible adverse impacts, such as:

(1) Changes in surface water flow patterns

(2) Decreased surface water flow

(3) Lowering of the groundwater table

(4) Pollution of ground and/or surface water

In general, a person holding appropriative water rights may invoke his rights of protection "against acts of persons holding lesser rights, or without right, that result in materially diminishing the quantity or depreciating the quality of the water for his proper purposes, or that interfere with the streamflow at the times he is entitled to it" (56). In addition, "his right of protection may also be invoked against the acts of those with equal rights, or even against those with greater rights" (56). This statement, in effect, would give grounds for a person to sue for damages if any of the above impacts due to subsidence infringed on that persons' water rights. Concerning water quality alone, a person is entitled to his appropriated amount of water in such a state of natural purity as to substantially fulfill the purposes for which his appropriation was made" (56). In all seven western states in the study area, it is up to the owner of the water rights which have been affected to prove who caused the damages and the extent of the damages before any retribution can be made.

If it is deemed by the courts that a person has suffered damage to his water rights due to the actions of another party, (such as a mining company causing subsidence) there are a number of legal remedies which may be invoked. In general, a person may be granted an injunction or compensation for damages. Compensation for damages may be in the form of some monitary settlement or the party causing the damages may be forced to provide water from another source. The following court cases deal with such incidents:

(1) Rogers versus Nevada Canal Company, 60 Colo. 59, 64, 151 Pac. 923 (1915)

(2) Tucker versus Missoula Light and Ry. Company, 77 Montana. 91, 97-99, 250 Pac. 11 (1926)

(3) Grand Valley Irrigation Company versus Lesher, 28 Colo. 273, 284, 65 Pac. 44 (1901)

Another aspect in any water rights consideration is that the U.S. Office of Surface Mining's reclamation and enforcement regulations are designed to minimize the impacts of underground coal mining on hydrology. The current regulations state that, "under ground mining activities shall not be conducted beneath or adjecent to any perennial stream, or impoundment having a storage volume of 20 acre-feet or more unless the regulatory authority... determines that subsidence will not cause material damage to streams, water bodies and associated structures" (57) In addition, mining "beneath any aquifer that serves as a significant source of water supply to any public water system shall be conducted so as to avoid disruption of the aquifer" (57). Section 817.52 of the regulations requires ground and surface water monitoring around an underground mining site. Such monitoring is designed to predict and prevent adverse impacts to the hydrologic system in the area of the mining. This monitoring data might also be used to determine if water rights infringements have occured.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Thick Coal Seams in the Western United States

Of the seven western states surveyed, Montana, Colorado, Wyoming, New Mexico, and Utah were found to have underground mineable coal seams which are 15 feet or more thick. The fields in Colorado and Utah will probably be the first to be mined using underground thick seam methods, whereas many of the fields in Montana and Wyoming contain coal beds which can be surface mined first.

Foreign Literature

No complete case histories were found which directly addressed all of the study criteria, namely underground total extraction mining of thick coal seams and the consequent hydrologic impacts. The British literature contained, by far, the most directly applicable, useable information. Other useful information on various aspects of subsidence due to underground mining and its effects on hydrology was found from a number of additional countries. These countries included primarily India, Yugoslavia, New Zealand, and Australia.

Effects on Hydrology

Table 4 lists the parameters associated with each of the ten square mile areas and ten single panels. In the analysis of both the single panels and the square mile sites, it was found that the largest strata disruptions, and consequently hydrologic impacts, occured when large extracted seam thicknesses were coupled with shallow overburden depths.

Figure 58 is a graph of maximum profile slope, G, versus the extracted seam thickness to overburden depth ratio, m/h. As can be seen, a log-log plot of these variables shows a strong linear relationship. The circled points indicate those single panels where w/h was considerably less than critical so that

TABLE 4. - Parameters for the ten site analyses

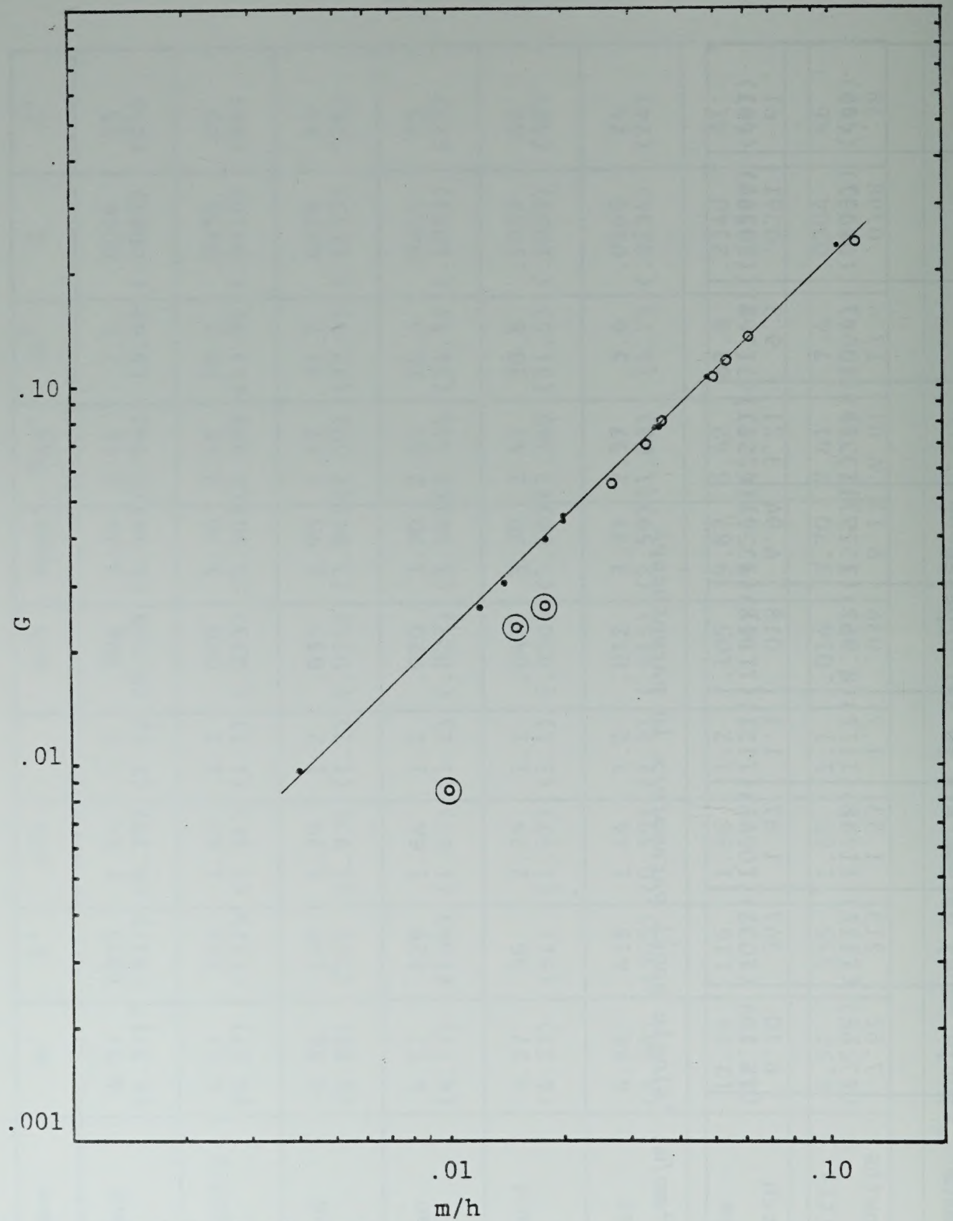
Field Name	m[1]	h[1]	w/h	g	m/h	S_{SEH}[1]	S_{KS}[1]	$+E$[2]	G	$\dot{C}$[1]
North Park	4.57 (4.57)[3]	1053 (437)	1.14 (0.39)	1.2 (1.2)	.004 (0.10)	3.70 (1.44)	2.41 (0.94)	2.1 (5.4)	.0096 (.0087)	23 (23)
Birney-Broadus	4.57 (4.57)	225 (137)	1.62 (1.31)	1.1 (1.1)	.020 (.033)	3.70 (3.54)	2.41 (2.30)	10.2 (17.8)	.0451 (.0710)	46 (46)
Moorhead	4.88 (4.88)	140 (91)	1.79 (1.97)	1.2 (1.2)	.035 (.054)	3.95 (3.84)	2.57 (2.50)	21.2 (33.6)	.0776 (.1155)	24 (24)
Sheridan	4.57 (4.57)	229 (168)	1.64 (1.07)	1.2 (1.2)	.020 (.027)	3.70 (3.41)	2.41 (2.34)	10.4 (31.5)	.0444 (.1083)	23 (23)
Fruitland	4.57 (4.57)	96 (91)	2.29 (1.97)	1.1 (1.1)	.048 (.050)	3.70 (3.60)	2.41 (2.34)	30.8 (31.5)	.1059 (.1083)	46 (46)
Kemmerer	4.88 (4.88)	418 (305)	1.44 (0.59)	1.2 (1.2)	.012 (.015)	3.95 (2.59)	2.57 (1.68)	5.6 (6.7)	.0260 (.0234)	24 (24)
Gillette	12.19 (12.19)	116 (107)	1.96 (1.69)	1.2 (1.2)	.105 (.114)	9.87 (9.54)	6.42 (6.20)	63.8 (71.6)	.2340 (.2459)	61 (61)
Book Cliffs	4.57 (4.57)	335 (122)	1.67 (1.48)	1.1 (1.1)	.014 (0.37)	3.70 (3.56)	2.41 (2.31)	7.4 (20.4)	.0304 (.0803)	46 (46)

[1]meters, [2]mm/m, [3]single panel parameters in parentheses

TABLE 4. - Parameters for the ten site analyses (continued)

Field Name	m[1]	h[1]	w/h	g	m/h	S_{SEH}[1]	S_{KS}[1]	+E[2]	G	C[1]
Kaiparowits	7.62 (7.62)	213 (122)	1.53 (1.48)	1.2 (1.2)	.036 (.062)	6.17 (5.97)	4.01 (3.88)	17.4 (36.7)	.0798 (.1347)	38 (38)
Wasatch	6.10 (6.10)	347 (335)	1.67 (0.54)	1.1 (1.1)	.018 (.018)	4.94 (3.24)	3.21 (2.11)	9.5 (7.8)	.0391 (.0266)	61 (61)

[1] meters, [2] mm/m, [3] single panel parameters in parentheses



•- Total mined area
o- Single panel

FIGURE 58. - Maximum profile slope, G, versus extracted seam thickness - overburden depth ratio, m/h, for the ten analyzed sites.

S_{SEH} was significantly less than S_m in equation 3.

Figure 59 is a plot of maximum tensile strain, +E, versus m/h. Here to, the log-log plot shows a good linear relationship indicating that, for the analyzed sites, +E increases directly with m/h.

As shown by equation 8, height of caving, C, is directly proportional to the swell factor, g. C is particularly sensitive to g in that a .1 increase in g can result in doubling of C for a given value of m (note North Park versus Birney-Broadus in table 4). For this reason, in cases where there is some doubt, g should be estimated on the low side to provide a margin of safety.

Maximum subsidence and the subsidence profile were found to be a function of the panel width-depth ratio within a given overburden lithology. The methods used to compute S_{SEH} and the SEH profile were based on empirical data from the British Coal Measures. The comparison of S_{SEH} and the SEH profile to S_{KS} and the KS profile shows the differences which can be expected between areas of weak and areas of strong overburden. Since +E and G are largely a function of the shape of the subsidence profile these parameters too can be expected to be, in part, a function of overburden lithology.

Groundwater quality should not be degraded by thick seam underground mining methods which maximize coal recovery and subsidence, to a greater degree than by room and pillar and longwall methods presently used, or by surface mining. The primary effect on surface water quality may be an increase in stream sediment load owing to changes in channel and drainage surface slope.

The primary changes to surface water quantity and flow patterns would occur through:

(1) Ponding in the subsidence trough;

(2) changes in channel slope; and

(3) loss of surface water owing to seepage into surface fissures.

Groundwater quantity and flow patterns may be altered by:

(1) Increases in the permeability of the groundwater media; and

(2) creation of new hydraulic connections between previously isolated aquifers.

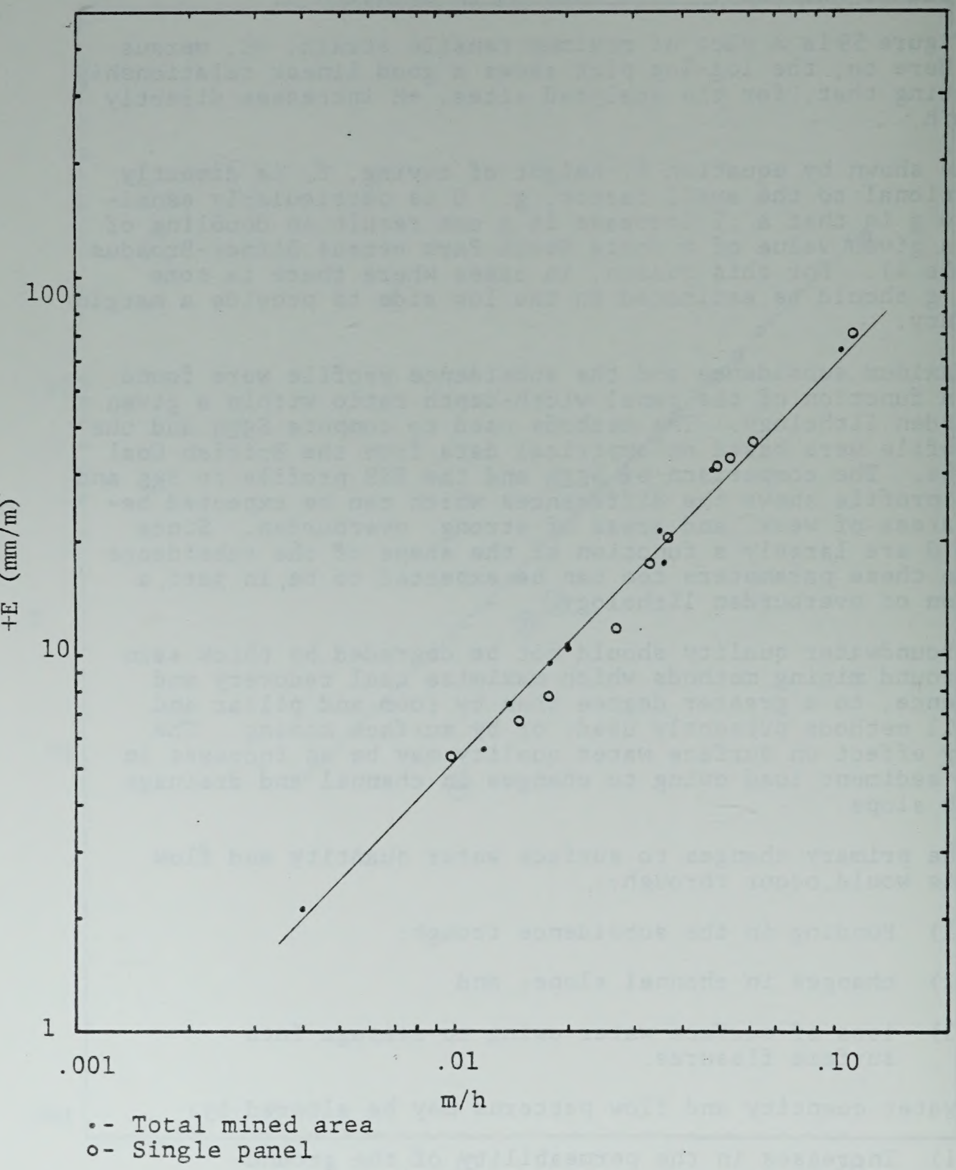


FIGURE 59. - Maximum tensile strain, +E, versus extracted seam thickness - overburden depth ratio, m/h, for the ten analyzed sites.

Given the semiarid climate in the western United States and the often sparce ground and surface water resources, the total hydrologic impacts of underground thick seam mining may often be small in comparison to a more humid climate. However, these impacts may still be significant in the context of the great importance attached to water in the west.

Recommendations

Since little hard data is available concerning the hydrologic impacts of the underground near-total extraction mining of thick coal seams, the following areas need to be investigated further:

(1) Surveying of existing longwall mines in the western U.S. to obtain data for the development of a subsidence prediction methodology more applicable to the higher strength overburdens found in the western U.S.;

(2) hydrologic monitoring of an active longwall mine in the west to measure impacts; and

(3) a more detailed site analysis involving: the most likely sites in the west where this type of mining would take place; formulation of a detailed mining plan for the site; and collection and analysis of more detailed stratigraphic and hydrologic baseline data.

Inventions

No inventions were developed as a result of this contract.

SECTION VII

REFERENCES

1. Dunham, R.K. Thick Seam Mining - A Review of the Methods. World coal, v. 4, No. 10, October 1978, pp. 24-27.

2. Utah Geological and Mineralogical Survey. Coal Monograph Series, No. 1-3, 1972.

3. Kiilsgaard, T.H. The Geology and Coal of the Horseshoe Creek District, Teton County, Idaho. Idaho Bureau of Mines and Geology, Pamphlet 92, 1951.

4. National Coal Board. Subsidence Engineers' Handbook. National Coal Board Mining Department, Great Britain, 1975, 111 pp.

5. Dunrud, C.R. Some Engineering Geologic Factors Controlling Coal Mine Subsidence in Utah and Colorado. U.S. Geological Survey Professional Paper 969, 1976, 39 pp.

6. Zwartendyk, Economic Aspects of Surface Subsidence Resulting from Underground Mineral Exploitation, Ph.D Thesis, Pennsylvania State University, 1971, 411 pp.

7. Kumar, R., and B. Singh. Mine Subsidence Investigations Over a Longwall Working and the Prediction of Subsidence Parameters for Indian Mines. International Journal of Rock Mechanics Min. Sci. & Geomech. Abstr., v. 10, 1973, pp. 151-172.

8. Kapp, W.A. The Characteristics of Subsidence Due to Underground Coal Mining at Newcastle, New South Wales. Proceedings of the Second International Symposium on Land Disturbance, IAHS-AISH, Publication No. 121, 1976.

9. Gentry, D.W., and J.F. Abel. Rock Mass Response to Mining Longwall Panel 4N, York Canyon Mine. Mining Engineer, v. 30, No. 3, 1977, pp. 273-280.

10. Mohr, H.F. Influence of Mining on Strata. Mine and Quarry Engineering, v. 22, No. 4, 1956, pp. 140-152.

11. Wardell, K. The Effects of Mineral and Other Underground Excavations on the Overlying Ground Surface. Proceedings of the Symposium on Geological and Geographical Problems of Areas of High Population Density, Washington, D.C., 1970, pp. 201-217.

12. Orchard, R.J. The Control of Ground Movements in Undersea Workings. The Mining Engineer, v. 28, No. 101, Part 5, pp. 259-273.

13. Singh, T.N., and B. Singh. Load and Convergence Measurements in Worked Out Areas in Mines - A Critical Review. Journal of Mines, Metal, and Fuels, January 1971, pp. 7-21.

14. EDAW, Inc., and Earth Sciences Associates. Environmental and Economic Effects of Subsidence. LBL-8615, GSRMP-1, VC-66e, DOE Contract W-7405-ENG-48, May 1979.

15. Coleman, A. Land Reclamation at a Kentish Colliery. Transactions of the Institute of British Geography, 21, 1955, pp. 117-135.

16. Wohlrab, B. Effects of Land Subsidences Caused by Mining to the Groundwater and Remedial Measures. Land Subsidence, Proceedings of the Tokyo Symposium, 1969, pp. 502-511.

17. Sovinc, I. Geotechnical Aspects of Longwall Face Caving. Proceedings of the Third Congress of the International Society for Rock Mechanics, v. II, Part B, pp. 1096-1107.

18. Leopold, L.B., and M.G. Wolman. River Channel Patterns: Braided, Meandering, and Straight. U.S. Geological Survey Professional Paper 282-B, 1957.

19. Friedkin, J.F. A Laboratory Study of the Meandering of Alluvial Streams. U.S. Army Corps of Engineers Waterways Experiment Station, 1945, p. 40.

20. Land, E.W. A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material. M.R.D. Sediment Series No. 9, U.S. Army Engineer Division, Missouri River, Corps of Engineers, Omaha, Nebraska, 1957.

21. Ackers, P., and F.G. Charlton. The Geometry of Small Meandering Streams. Proceedings of the Institute of Civil Engineers, Paper 73285, 1970, pp. 289-317.

22. Simons, D.B., P.F. Lagasse, Y.H. Chen, and S.A. Schumm. The River Environment, a Reference Document. prepared for the U.S. Department of the Interior, Fish and Wildlife Service, Twin Cities, Minnesota, 1975.

23. Schumm, S.A. 1960. The Effect of Sediment Type on the Shape and Stratification of Some Modern Fluvial Deposits. American Journal of Science, v. 258, p. 177-184.

24. Roll, R.J. Effect of Subsidence on Well Fields, Journal of American Water Works Association, v. 59, No. 1, 1967, pp. 80-88.

25. Schumann, H.H., and J.F. Poland. Land Subsidence Earth Fissures and Groundwater Withdrawal in South-Central Arizona, U.S.A. Institute of Scientific Hydrology, Proceedings: Reading Symposium on World Water Balance, July 1970.

26. Nishida, T., and K. Goto. Damage to Irrigation Ponds Due to Mining Subsidence. Land Subsidence, Proceedings of the Tokyo Symposium, 1969, pp. 496-501.

27. McKee, J.E., and H.W. Wolf. Water Quality Criteria. California State Water Quality Control Board, Publication No. 3-A, Sacramento, California, 1963.

28. Hill, R.D. Non-Point Pollution From Mining and Mineral Extraction. Non-Point Sources of Water Pollution, Proceedings of a Southeastern Regional Conference, Virginia Water Resources Research Center, Blacksburg, Virginia, May 1975.

29. Wischmeier, W.H., and D.D. Smith. Predicting Rainfall-Erosion Losses - A Guide to Conservation Planning. U.S. Department of Agriculture, Agriculture Handbook No. 537, 1978.

30. Thomas, J.L. An Introduction to Mining - Exploration, Feasibility, Extraction, Rock Mechanics. Holstead Press, New York, 1978.

31. Wilson, A.H. Various Aspects of Longwall Roof Support. Colliery Guardian, v. 226, No. 4, pp. 50-54.

32. Ropski, S., and R.D. Lama. Subsidence in the Near-Vicinity of a Longwall Face. International Journal of Rock Mechanics Min. Sci. and Geomech. Abstracts, v. 10, pp. 105-118.

33. Kenney, P. The Caving of the Waste on Longwall Faces. International Journal of Rock Mechanics Min. Sci., v. 6, 1969, pp. 541-555.

34. Hrastnik, L. Problems of Determining the Safe Thickness of Impermeable Clay Layers Between Coal Seams and Water-Bearing Sand Layers in the Hanging Wall. Rudarsko-Metalurski Zbornik, No. 1, pp. 45-47.

35. Nakajima, S. Thick Seam Mining Techniques in Japan. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 21-40.

36. Saxena, N.C., S. Samanta, K.P. Mukherjee, and B. Singh. Strata Control Investigations at Caved Longwall Faces with Special Reference to the Faces of Moonidih Project. Journal of Mines, Metals, and Fuels, March 1978, pp. 109-130.

37. Stefanko, R. Coal Mining in the U.S.A. Rough Draft of a Report Sponsored in Part by Hittman Associates, Inc., Electric Power Research Institute (EPRI), and the Mining Enforcement Safety Administration (MESA), pp. 35-42.

38. Harrison, C. Mining the Thick Seams of the South Maitland Coalfield, N.S.W. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 1-13

39 Sikora, W. Methods for Working Thick Seams and Research on Increasing Their Effectiveness. Symposium of Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 93-106.

40. Dierks, H.A., W.C. Eaton, R.H. Whaite, and F.T. Moyer. Mine Water Control Program, Anthracite Region of Pennsylvania: July 1955 - December 1961. U.S. Bureau of Mines, Information Circular 8115, 1962, 63 pp.

41. WIlliamson, W.H. Hydrogeological Aspects of Coal Mining Under Stored Waters near Sydney, Australia. SIAMOS - 78, Granada, Spain, 1978, pp. 309-328.

42. Neate, C.J., and B.N. Whittaker. Influence of Proximity of Longwall Mining on Strata Permeability and Groundwater 20th U.S. Symposium on Rock Mechanics, Austin, Texas, June 4-6, 1979, pp. 217-224.

43. Whittaker, B.N., R.H. Singh, and C.J. Neate. Investigation and Evaluation Studies of Surface and Subsurface Drainage Pattern Changes Resulting from Longwall Mining Subsidence. First International Mine Drainage Symposium, Denver, Colorado, May 20-23, 1979.

44. Horslev, M.S. Time Lag and Soil Permeability in Ground Water Measurements. U.S. Army Corps of Engineers Waterways Experiment Station, Bulletin 36, 50 pp.

45. Whittaker, B.N., and R.N. Singh. Design Aspects of Barrier Pillars Against Water-Logged Workings in Coal Mining Operations. Symposium on Water in Mining and Underground Works, SIAMOS - 78, v. 1, Granada, Spain, 1978, pp. 675-692.

46. Musser, J.J. Acid Mine Drainage in the Appalachian Region. U.S. Geological Survey, Hydrologic Atlas HA-198, sheet 9, 1965.

47. Hamilton, D.A., and J.L. Wilson. A Generic Study of Strip Mining Impacts on Groundwater Resources. Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, Massachusetts Institute of Technology, Report No. 229, 1977.

48. Van Voast, W.A., and R.B. Hedges. Hydrogeologic Aspects of Existing and Proposed Strip Coal Mines Near Decker, Southeastern Montana. State of Montana Bureau of Mines and Geology, Bulletin 97, 1975.

49. Davis, R.W. Hydrologic Factors Related to Coal Development in the Eastern Powder River Basin. Twenty-eighth Annual Field Conference, Wyoming Geological Association Guidebook, 1976.

50. Hittman Associates, Inc. Monitoring and Modeling of Shallow Groundwater Systems in the Powder River Basin, Second Annual Technical Report. H-D0166-78-757F, Prepared Under U.S. Bureau of Mines Contract No. J0265050, February 1979.

51. Van Voast, W.A., R.B. Hedges, and J.J. McDermott. Completion Report, Hydrologic Characteristics of Coal Mine Spoils, Southeastern Montana. Montana University Joint Water Resources Research Center, Report No. 94, June 1978.

52. Hounslow, A.W., J. Fitzpatrick, L.A. Cerrillo, and M. Freeland. Overburden Minerology as Related to Ground Water Chemical Changes in Coal Strip Mining. Proceedings of the Symposium of Surface Mining Hydrology, Sedimentology, and Reclamation, Lexington, Kentucky, December 1979, pp. 161-168.

53. American Jurisprudence. v. 78, 2nd series.

54. Ranquist. The Winters Doctrine and How It Grew: Federal Reservation of Rights to the Use of Water. B.Y.U. Law Review 643, 1975.

55. Colorado Revised Statutes. Articles 80 through 92, 1973.

56. Hutchins. Water Rights in the Nineteen Western States. v. II, U.S. Department of Agriculture, Pub. No. 1206, 1974.

57. Surface Coal Mining and Reclamation Operations, Permanent Regulatory Program. Federal Register, v. 44, No. 50, March 13, 1979.

37. Stefanko, R. Coal Mining in the U.S.A. Rough Draft of a Report Sponsored in Part by Hittman Associates, Inc., Electric Power Research Institute (EPRI), and the Mining Enforcement Safety Administration (MESA), pp. 35-42.

38. Harrison, C. Mining the Thick Seams of the South Maitland Coalfield, N.S.W. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 1-13

39 Sikora, W. Methods for Working Thick Seams and Research on Increasing Their Effectiveness. Symposium of Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 93-106.

40. Dierks, H.A., W.C. Eaton, R.H. Whaite, and F.T. Moyer. Mine Water Control Program, Anthracite Region of Pennsylvania: July 1955 - December 1961. U.S. Bureau of Mines, Information Circular 8115, 1962, 63 pp.

41. WIlliamson, W.H. Hydrogeological Aspects of Coal Mining Under Stored Waters near Sydney, Australia. SIAMOS - 78, Granada, Spain, 1978, pp. 309-328.

42. Neate, C.J., and B.N. Whittaker. Influence of Proximity of Longwall Mining on Strata Permeability and Groundwater 20th U.S. Symposium on Rock Mechanics, Austin, Texas, June 4-6, 1979, pp. 217-224.

43. Whittaker, B.N., R.H. Singh, and C.J. Neate. Investigation and Evaluation Studies of Surface and Subsurface Drainage Pattern Changes Resulting from Longwall Mining Subsidence. First International Mine Drainage Symposium, Denver, Colorado, May 20-23, 1979.

44. Horslev, M.S. Time Lag and Soil Permeability in Ground Water Measurements. U.S. Army Corps of Engineers Waterways Experiment Station, Bulletin 36, 50 pp.

45. Whittaker, B.N., and R.N. Singh. Design Aspects of Barrier Pillars Against Water-Logged Workings in Coal Mining Operations. Symposium on Water in Mining and Underground Works, SIAMOS - 78, v. 1, Granada, Spain, 1978, pp. 675-692.

46. Musser, J.J. Acid Mine Drainage in the Appalachian Region. U.S. Geological Survey, Hydrologic Atlas HA-198, sheet 9, 1965.

47. Hamilton, D.A., and J.L. Wilson. A Generic Study of Strip Mining Impacts on Groundwater Resources. Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Dept. of Civil Engineering, Massachusetts Institute of Technology, Report No. 229, 1977.

48. Van Voast, W.A., and R.B. Hedges. Hydrogeologic Aspects of Existing and Proposed Strip Coal Mines Near Decker, Southeastern Montana. State of Montana Bureau of Mines and Geology, Bulletin 97, 1975.

49. Davis, R.W. Hydrologic Factors Related to Coal Development in the Eastern Powder River Basin. Twenty-eighth Annual Field Conference, Wyoming Geological Association Guidebook, 1976.

50. Hittman Associates, Inc. Monitoring and Modeling of Shallow Groundwater Systems in the Powder River Basin, Second Annual Technical Report. H-D0166-78-757F, Prepared Under U.S. Bureau of Mines Contract No. J0265050, February 1979.

51. Van Voast, W.A., R.B. Hedges, and J.J. McDermott. Completion Report, Hydrologic Characteristics of Coal Mine Spoils, Southeastern Montana. Montana University Joint Water Resources Research Center, Report No. 94, June 1978.

52. Hounslow, A.W., J. Fitzpatrick, L.A. Cerrillo, and M. Freeland. Overburden Minerology as Related to Ground Water Chemical Changes in Coal Strip Mining. Proceedings of the Symposium of Surface Mining Hydrology, Sedimentology, and Reclamation, Lexington, Kentucky, December 1979, pp. 161-168.

53. American Jurisprudence. v. 78, 2nd series.

54. Ranquist. The Winters Doctrine and How It Grew: Federal Reservation of Rights to the Use of Water. B.Y.U. Law Review 643, 1975.

55. Colorado Revised Statutes. Articles 80 through 92, 1973.

56. Hutchins. Water Rights in the Nineteen Western States. v. II, U.S. Department of Agriculture, Pub. No. 1206, 1974.

57. Surface Coal Mining and Reclamation Operations, Permanent Regulatory Program. Federal Register, v. 44, No. 50, March 13, 1979.

APPENDIX A

IDENTIFIED WESTERN THICK SEAM COAL FIELDS

Denver Basin Fields

Location

The Denver Basin covers an area of about 5700 square miles in eastern Colorado east of the Front Range, extending from near Colorado Springs, north to just south of Greely. It extends eastward from the Front Range to near Limon. The general outline of the basin is roughly oval with its long axis trending north-south.

Topography

Topographically, the basin is characterized by undulating plains, locally dissected by stream erosion. The climate is semiarid, vegetation consists principally of grasses.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - ?	Deposits of silt, sand, and gravel concentrated along stream channels.
Castle Rock conglomerate	0 - 300'	Andesite conglomerate with clasts up to 4' in diameter and arkosic and andesitic coarse sandstones.
Dawson arkose	1000 - 1800'	Lower member, 200 - 400' thick, contains both andesitic and arkosic material ranging from claystone to conglomerate. 800 to 1400' thick upper member is 70 to 90% arkosic sandstone and conglomerate interbedded with 10 to 30% sandy claystone.
Denver formation	600 - 1580'	Claystone, siltstone, very fine to fine-grained sandstone, and andesitic conglomerate. Lava flows interbedded near Golden.

Arapahoe formation	200 - 1000'	Basal conglomerate topped by thick beds of claystone, shale and siltstone interbedded with thin sandstones.
Laramie formation	350 - 900'	Brackish-water and continental sandstones, shales, claystones, and coals. Lower 100 - 300' predominantly medium-grained sandstone with interbedded coal and thin shale. Upper 250 to 600' primarily shale, siltstone, claystone and minor sandstone.

Structure

Structurally, the Denver Basin is a broad, gentle basin, steeper on the west flank along the uplifted mountain front. The margins of the Denver Basin region are defined by the outcrop of the coal-bearing basal part of the Laramie formation. Strata is well-exposed along the foothills hogbacks extending from near Colorado Springs to Boulder, where dips may be near-vertical but flatten rapidly to 5 degrees or less eastward into the basin.

Seams

The primary occurances of coal in the Denver Basin are in the upper Cretaceous Laramie formation and the Paleocene Denver formation. Laramie formation coal varies in rank form subbituminous B to lignite A. Known occurances of coal greater than 15 feet thick in the Laramie formation are in the Colorado Springs field and near Buick and Matheson on the east flank of the Denver Basin.

Colorado Springs Field

The Colorado Springs field is in central El Paso County, north and east of downtown Colorado Springs. At Colorado Springs, three seams, A, B, and C are recognized in the basal Laramie. Only the lowest, A seam, is thick, varying from about 5 feet to 17 feet.

Buick-Matheson Area

The Buick-Matheson area is in eastern Elbert County on the eastern margin of the Denver Basin mostly between the towns of Buick on the north and Matheson on the south. The coal zone averages 25 to 50 feet thick in this area and contains two notable coal beds. The upper of these beds is 10 to 25 feet above the lower, is 1 to 17 feet thick, but locally splits into as many as five thinner beds.

The Denver formation coals are primarily lignite A. Thick lignite beds occur in a zone in the upper 300 to 500 feet of the formation; about 800 to 1500 feet above the top of the Laramie coal zone. The Denver formation lignite zone can be divided into a northern and southern area, each witn it's own stratigraphy. The E bed of the northern area is the thickest and most continuous bed in the Denver formation. Gross thickness averages 20 to 30 feet (including partings) and ranges up to a maximum of 54.5 feet near Watkins. Lignite beds A through D are often 10 to 15 feet thick and locally are over 30 feet tnick. The Wolf bed is the thickest in the southern area, ranging from 18 to 28 feet thick. The lower southern area beds may locally be up to 24 feet thick but are typically in the 5 to 10 foot range.

Mining Conditons

Little is known about the nature of the Laramie formation coal towards the center of the basin. Where it is known to occur in thicknesses over 15 feet it is more suitably strip mined than underground mined. Most of the Denver formation lignite beds contain numerous non-coal partings. Parting thickness ranges from less than .1 inch to over 2 feet. Most of the thick lignite beds are within 200 feet of the surface and are strippable. Little is known about the lignite beds in the deeper, western portion of the basin. Existing data suggest the lignite beds thin, become carbonaceous, and may completely pinch out near the basin axis. This is significant in that it implies lignite beds are thinner and less abundant in areas where beds are deep enough to be mined underground.

Water Resources

The northern portion of the basin is drained by the North Platte River and its tributaries; the southern part by the Arkansas River and its tributaries. Numerous small reservoirs and irrigation ponds exist throughout the basin but particularly along the South Platte River which is the most important body of surface water in the area.

Prominant ground water sources include the Fox-Hills formation, the Arapahoe formation, and the Dawson arkose. The coals in the lower portions of the Laramie formation are often intimately associated with the Laramie - Fox Hills aquifer. In the eastern part of the basin the basal conglomerate of the Arapahoe formation is a section of strata which is an excellent high-permeability aquifer and generally contains high-quality water. Denver formation lignites are directly below the Dawson arkose, a prolific water-producing formation, and above sandstones which provide small quantities of water from the lower Denver formation.

North Park Field

Location

Located in North Park Basin in north-central Colorado. Bounded on the south and west by the continental divide, on the east by the Medicine Bow Mountains, and on the north by the Colorado-Wyoming State line. North Park occupies approximately 1,400 square miles.

Topography

The basin is surrounded on all sides by uplands against which the edges of coal bearing strata have been upturned and eroded. The terrain of the basin can best be described as gently rolling with local flexures causing coal seams to exposed in the inner portion of the basin as well as around its edges.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Unconsolidated sediments	0 to hundreds of feet	Alluvium, dune sand, terrace gravel, glacial silt, sand, and boulders.
North Park formation	600'	Shale, sandstone, volcanic ash, tuff, and conglomerate.
Coalmont formation	4000-6000'	Sandstone, conglomerate, shale, and coal beds.

Structure

The sedimentary rocks of North Park form a synclinal trough which lies between the uplifted crystalline masses of the Medicine Bow Range on the east and the Park Range on the west. On the north the syncline is terminated by a great fault and on south sedimentary strata rise on the uplift which forms the divide between North and Middle Parks. The strata of the park floor are broken by number of significant fault sets as well as many smaller faults of lesser displacement and extent. Faulting and folding have exposed coal beds in the northeastern, northwestern, and southwestern part of the field. Dips are generally high in the areas where coal beds are exposed. At some coal outcrops in the northeastern corner of the field beds have been overturned and dips are nearly vertical.

Seams

The principal thick seams in the field are the Riach and Suddeth seams of the Coalmont formation. The Riach seam is exposed in the southwest portion of the field near Coalmont. This seam is 22 to 77 feet thick and has been mined fairly extensively. It is however, extensively block faulted and tilted. The Suddeth seam is exposed on the flanks of the McCallum anticline in the northeast part of the field near Walden. It occurs in thicknesses of 10 to 58' and has dips ranging from 20 to 85 degrees.

Mining Conditions

Conditions for longwall-type mining in the Riach seam near Coalmont are complicated by high dips and complex faulting. For this reason, the best prospects for mining exist in the Suddeth seam which is more uniform and continuous although possessing medium to high dip angles. The extreme thickness of the seam in some portions may permit longwall mining along the strike in horizontal panels.

Water Resources

The North Platte River drains the entire field. Surface water is readily available in its many tributaries which infringe upon almost all areas of the field. These include the Canadian River, Michigan River, Illinois Creek, Grizzly Creek, Norris Creek and Roaring Fork. Lakes include Lake John and Boetcher Lake. The northeast corner of the field,in the vicinity of the Suddeth seam outcrops, is tranversed by the extensively braided Michigan River and the Canadian River.

There is much potential for groundwater because of the presence of large amounts of alluvium and glacial material which are capable of absorbing a good percentage of the precipitation and the surface water present in the field.

Somerset Field

Location

The Somerset field is located in parts of Delta and Gunnison Counties in western Colorado near the town of Paonia. It is bounded by the Grand Mesa coalfield on the west and the Crested Butte field on the east. Coal outcrops along the North Fork of the Gunnison River.

Topography

The area is mountainous with high relief. Coal outcrops are generally along the valley bottoms affording little opportunity for surface mining. Overburden depths show large variations across the field due primarily to topographic effects. Slopes range from about 3 to about 65 percent.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and colluvium	up to 200'	Unconsolidated material deposited by fluvial processes or gravity.
Ruby formation	200'+	Shales, sandstones, and conglomerates.
Undifferentiated member of the Mesa Verde formation	1600'	Lenticular sandstones with subordinate interbedded shales.
Paonia member of the Mesa Verde formation	300 - 500'	Equal portions of shale and interbedded lenticular sandstone. Two coal horizons including the thick Oliver or D bed.
Bowie member of the Mesa Verde formation	270 - 350'	Shale with thin to thick lenticular beds of coal including the thick Somerset or B bed.

Rollins member of the Mesa Verde formation	120 - 200'	Massive medium to coarse grained sandstone.

Structure

Structure consists of a series of sediments which exhibit a low regional dip (5 degrees) to the northeast. The strata is intruded in some places by igneous plugs, dikes, and sills. Minor faulting of a localized nature is present within the field.

Seams

The two seams reaching thicknesses in excess of 15' are the Oliver or D seam and the Somerset or B seam. The D horizon occurs immediately above the massive sandstone marker bed at the top of the Bowie member. The D horizon has been divided into four distinct seams, the D-1A, D-1, D-2, and D-3 beds. The D-2 locally reaches thicknesses of about 16'. The B seam is in the Bowie member from 20 to 120' above the Rollins sandstone. In the Somerset-Hawksnest area the B seam reaches a maximum thickness of 24'. In the Hubbard Creek area the B splits into the B-1 and B-2. The B-1 is from 14 to 15' thick and the B-2 is up to 21'.

Mining Conditions

The high relief and steep topography as well as thick overburden severly limit the possibilites for surface mining. Local igneous intrusives and faulting will create some difficulties in underground mining. Little information is available concerning the continuity of the thick seams throughout the field.

Water Resources

The North Fork of the Gunnison River is the largest surface stream in the field. At a point near Somerset it has a drainage area of about 251 square miles and an average annual flow of 438 cfs of which over 75 percent occurs during the spring snowmelt runoff period. A number of smaller perennial streams tributary to the North Fork of the Gunnison also exist in the area. Paonia reservoir is located on the North Fork of the Gunnison just upstream from Somerset.

Groundwater is present in the alluvium along the streams and creeks of the area as evidenced by springs and seeps. The coal seams as well as the thick sandstone units of the Paonia and Bowie members have potential for groundwater.

Yampa Field

Location

Located in the Green River Region of northwest Colorado. Its eastern border is just east of Steamboat Springs. The field includes most of townships 3 through 9 N and ranges 84 through 94 W.

Topography

Topography of the Green River Region ranges from a broad plateau containing numerous mesas, tablelands, and fertile valleys in the west to high mountains in the east. Elevations range from 5,400 to 12,065 feet above sea level.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and Volcanics	0 - ?	Silts, sands, and gravels along streams and local deposits of Tertiary intrusives and volcanics.
Brown's Park formation	0 - 2000'	Fluvial siltstone, claystone, and conglomerate, loosely consolidated eolian sandstone, and volcanic ash. Bouldery in places, conglomerate at base. Occurs locally in the northern and western portions of the field.
Wasatch formation	maximum 5000'	Fluvial arkosic sandstone, mudstone, and conglomerate.
Fort Union formation	1500'	Sandstone, shale, and coal.
Lance formation	1000 - 1500'	Interbedded shale, sandstone and coal.
Lewis shale	2000'	Homogeneous marine shale.
Williams Fork formation	1100 - 2000'	Sandstone, shale, and coal.

Structure

The coal bearing rocks crop out along the Yampa River drainage area. The structure of the Green River region is relatively simple; however, folding and faulting have created areas of local complexity. Formation dips range from horizontal to vertical. Relatively gentle local folding along the south edge of the basin grades into more complicated structures eastward. On the southeast and east rims of the basin, local folding is complex and complicated by faulting and minor intrusives. Locally, the intrusives and structural deformation have increased the rank of the coals to anthracite.

Seams

The thick coals occur in lower part of the Williams Fork formation (Upper Cretaceous), the Paleocene Fort Union formation, and the continental Eocene Wasatch formation. The seams in the lower Williams Fork are labeled F through J and correlate with the Fairfield group in the Meeker area. Here the H is also called the Wolf Creek seam, I the Wadge, and J the Lennox seam, with the names used more commonly than the letters. The F and G zones are 10 to 16 feet locally and include multiple seams in the western part of the field. At mines west of Hayden the Wolf Creek ranges from about 9 to 19 feet. South of Craig and east of Hamilton, in the Williams Fort Mountains area, the J or Lennox zone is composed of multiple seams with thicknesses ranging from about 4 to 22 feet and with local names such as Searcy Gulch seam and Kellogg seam. The Wolf Creek zone has multiple seams of 3 to 15 feet which in one locality coalesce to a thickness of 42 feet with only minor partings. This group of coals, where not locally metamorphosed, generally is high-volatile C bituminous. The Seymour seam, a 10 to 17 feet thick coal near the top of the Fort Union formation has been mined at four locations about 11 miles northeast of Craig. This is bituminous B or C coal. The Wasatch coals are lenticular and are thought to range from 6 to 20 feet in thickness. Generally they are subbituminous B and C.

Mining Conditions

The Yampa field occurs at the extreme southeast edge of the Washakie basin where the geology is most complex. Local changes in dip and displacement of coal seams are a possible consequence of folding and faulting. In addition, little data is available concerning the areal extent of seams in excess of 15 feet but preliminary indications are that they are lenticular with significant thicknesses occuring only locally.

Water Resources

Western portions of the region are quite arid, recieving little precipitation (12.54 inches annual average in Craig) and containing sparse vegetation. The more mountainous eastern parts of the region average about twice as much precipitation and are more heavily vegetated. Groundwater is most likely to occur in significant quantities in the Fort Union and Wasatch formations. The conglomeratic portions of the Brown's Park formation are also likely to produce significant groundwater.

Of larger importance in the area are the numerous perennial surface streams issuing from the nearby mountains. Largest of these is the Yampa River itself which flows toward the west through the field. Of secondary but local importance are the numerous small tributaries which intersect the Yampa all along its length.

Ashland Field

Location

The field occupies 975 square miles in southwest Custer County, southeast Rosebud County, and northwest Powder River County in southeast Montana. Its northern boundary is 25 miles south of Miles City and its southern boundary is 30 to 40 miles north of the Montana-Wyoming state line.

Topography

The surface consists of a series of great benches resulting from the effects of erosion on flat lying strata with varying degrees of resistance. Elevations range from 2,650 feet on the Tongue River to a high of 4350 feet.

Lithólogy

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace deposits	0 - 90'	Coarse gravel, sand, and silt along stream channels.
Tongue River member of the Fort Union formation	1300 - 1750'	Massive sandstone, sandy shale, shale, and coal beds.

Structure

The strata are nearly horizontal. The chief structural features of the field are a broad syncline plunging gradually northeastward, its axis following the Tongue River valley, and a northwest trending downfold that crosses the Tongue River syncline near Ashland.

Seams

The coal is ranked as subbituminous. The Knoblock, E, A, Terret, Sawyer, and Rosebud beds all exceed 15 feet for some part of their extents. The most significant of these by far is the Knoblock coal which is estimated to contain some 46,210 acres of coal averaging 15 feet or more in thickness mostly found in the west central portion of the field on either side of the Tongue River. The other thick seams average 15 feet or more in thickness for the following amounts of acerage: Rosebud - 1,010, Sawyer - 3,464, Terret - 20, E - 433, and A - 1,795.

Mining Conditions

The beds generally have low dips and are not significantly faulted. Much of the coal lies under shallow enough overburden to be surface mined. A significant portion of the thick coal, most notably portions of the Knoblock seam, lies under deep enough overburden to make it a candidate for underground mining.

Water Resources

The Tongue River is the most significant body of surface water which occurs in the field. Parts of Rosebud Creek, Pumpkin Creek, and Little Pumpkin Creek also flow through the field and are of significant importance.

Primary bedrock sources of groundwater would be the coal seams and sandstone units of the Fort Union formation. Water would also be expected to occur in the alluvium and terrace gravels along stream channels.

Birney - Broadus Field

Location

Includes about 850 square miles in Rosebud and Powder River counties in southeastern Montana. Bounded on the east by the Powder River, on the northwest by the Tongue River. North-south width of about 25 miles.

Topography

The surface is deeply trenched by long, narrow valleys with precipitous slopes in many places, interrupted in some places by prominent topographic benches. Divide areas are mostly high and narrow except in southwest where the divide between the Tongue River and Otter Creek is a broad tableland. Maximum relief is 300 feet in the northeast to 1300' feet in the west.

Lithology

In sequence from surface units down to lowermost thick coal-bearing units.

Rock Units	Thickness	Description
Alluvium	?	Deposits ranging from cobbles and pebbles to gravel, sand, silt, and clay along the main streams and their tributaries.
Terrace gravels	?	Deposits of sand and gravel at different levels above main streams and larger tributaries.
Tongue River member of the Fort Union formation	1,475-1,650'	Sandy shale, shale, numerous coal beds and massive, crossbedded sandstone layers as much as 100 feet thick.

Structure

Strata are mostly flat lying with local dips up to 5 degrees. In the western part of the area strata dip gently northwest, in the southern to north-central areas dips are less than 1 degree southwesterly. Several southeast trending faults with displacements from 40 to 125 feet occur in the eastern portion of the field. A normal fault crosses the Tongue River in sections 7 and 8, T5S, R43E.

Seams

The Broadus, Knoblock, Pawnee, Dunning, Cook and Garfield beds all exceed 15 feet in thickness for some part of their extent. By far the most extensive and important of these thick seams is the Knoblock. It averages more than 15 feet in thickness in parts of T4S R43E, T4S R44E, T5S R44E, T6S R44E, T4S R45E, T5S R45E, T6S R45E, T4S R46E, T5S R46E, T6S R46E, and T6S R47E. This amounts to about 205 square miles in the western half of the field. The aerial extent of coal in excess of 15 feet thick for the other seams is: Broadus, 24 square miles, Pawnee, 74 square miles, Dunning, unknown but minimal, Cook, 24 square miles, and Garfield, 8 square miles. These figures include only coal with 1000 feet of overburden or less. The coal of the Birney - Broadus field is classified lignite.

Mining Conditions

Dips are very low reaching a local maximum of 5 degrees. Faulting is of minor importance and should not be a serious hindrance to mining. Much of the coal is near the surface and therefore more suitable for surface mining. The Knoblock and Broadus seams are among the lowest in the sequence and therefore the most likely to become candidates for underground mining in areas where overburden depths preclude surface mining.

Water Resources

The western two-thirds of the field is drained by the Tongue River and some of its tributaries. The rest is drained by the Powder River flowing along its western edge. Otter Creek is a larger tributary of the Tongue which flows through the central portion of the field. Hanging Woman Creek and Pumpkin Creek are also important tributaries of the Tongue River that intrude upon the field.

Groundwater may be found in the sandstone and coal beds of the Fort Union formation as well as in the alluvium along the stream channels.

Coalwood Field

Location

An area of about 650 square miles in the northeast corner of Powder River County. It extends about 18 miles south from the Custer County line and about 36 miles west from the Carter County line.

Topography

Total relief in the field is about 1000 feet with the highest point being at 3,835 feet on the Pumpkin Creek - Mizpah Creek divide and the lowest point on the Powder River at the north edge of the field. West of the Powder River the land surface has moderate to low relief. Broad valleys are separated by gently sloping divides which locally are moderately dissected forming sharper ridges, small mesas, or buttes. The slightly entrenched, meandering channel of the Powder River flows through an alluviated valley about 2 miles wide. East of the Powder River the slopes between the larger river valleys are gentle but locally dissected forming a landscape of somewhat less maturity.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - 30'	Flood-plain deposits and valley fill of silt, sand, and gravel in valleys of larger streams.
Terrace deposits	0 - 15'	Deposits of sand and gravel generally above and along stream channels.
Tongue River member of the Fort Union formation	750'	Thick bedded calcareous sandstones, shales, and carbonaceous shales, and persistent coal seams.

Structure

Most of the field lies on the crest and the west flank of a gently northwest-plunging anticlinal uplift. Most of the strata are nearly horizontal, dipping a degree or less in a northwesterly direction. Steeper dips may occur locally.

The coal is ranked as lignite, closely approaching subbituminous C. Thick coal occurs in the Tongue River member of the Fort Union formation. The Broadus bed is 15 feet 5 inches thick at the North Star mine in the southern portion of T2S, R50E. The Broadus bed is located 135 feet above the base of the Tongue River member of the Fort Union formation. Its largest extent is in the southwestern corner of the field where overburden depths often preclude surface mining. The Sawyer bed occurs above the Broadus bed in the Tongue River and reaches a thickness of 25 feet at the Ash Creek mine in T2S, R49E.

Mining Conditions

Dips are low and fairly consistant throughout the field. There is little data to assess the continuity of the seams but indications are that they are continuous where not eroded away although thicknesses may vary considerably over short distances. Faulting and folding are of little consequence in this field.

Water Resources

The Powder River is the only permanently flowing stream in the field although it is little more than a trickle in the driest months. Mizpah and Pumpkin Creeks flow most of the year but at times the only water is in standing pools and the channel gravels. Smaller tributaries are intermittent.

Clinker, coal, and the sandstone beds of the Fort Union formation are known to produce water. The alluvium along stream channels also has potential for groundwater production.

Eastward Extension of the Crow Indian Reservation Field

Location

This field is located in the eastern portion of Big Horn County, Montana. It includes outcrops of the coal bearing Wasatch and Fort Union formations on the western edge of the Powder River structural basin not included in other fields in Montana. The field includes townships 1 S to 10 S in the north-south direction and ranges 36 E to 38 E across its width.

Topography

The field is characterized by plains where the relief rarely exceeds 600 feet. The topography is dependent upon the underlying rocks. The shales give rise to broad flats and the more resistant sandstones form steep escarpments which roughly parallel the Big Horn Mountains to the west or follow the valleys of streams which have eroded into the bedrock.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace deposits	0 - 130'	Silts, sands, and gravels deposited along or above stream channels.
Wasatch formation	0 - 350'	Shale, sandstones, and some coal beds.
Tongue River member of the Fort Union formation	850 - 1800'	Shales, massive sandstones, and coal beds.

Structure

The area is in the western portion of the Powder River structural basin. The beds are nearly horizontal with generally slight dips away from the Big Horn Mountain uplift to the west. Minor structural complexities due to the western uplifts occur in the field but are of small local significance.

Seams

The coal is ranked as subbituminous. The Tongue River member of the Fort Union formation contains the thick coals in the field. Little information is available for assessing the thick coal seams in the field although a few outcrops do reveal coal in excess of 15 feet. These beds have not been correlated with beds in surrounding fields. Nearby areas do contain a total of about 11 coal seams which exceed 15 feet in thickness for some of their extent. Some of these seams probably persist into the subsurface of this field.

Mining Conditions

Dips are low and faulting is insignificant. Overburden depths can range from shallow to moderate depending upon where in the sequence the coal occurs. Much of the coal is probably strippable.

Water Resources

No significantly large perennial streams flow through the area. All streams are small tributaries to larger streams outside the field.

The Wasatch and Fort Union formations have sandstone and coal beds which are known to yield supplies of water adequate for domestic use in some parts of the Powder River basin. The alluvium in the stream valleys and the terrace deposits can yield significant supplies of highly mineralized water.

Forsyth Field

Location

The field covers an area of about 800 square miles in southern Montana, south of the Yellowstone River and east of the 107th meridian, and includes parts of Rosebud, Treasure, and Big Horn Counties.

Topography

The field can be characterized as a dissected plateau across which the Yellowstone River and its tributaries have cut valleys. In areas where the exposed rock is soft and erodible the uplands range from a subdued rolling surface to a rougher and minutely dissected surface where subject to stream erosion. In those areas where harder rock is predominant the divides are long and narrow and the intermittent streams flow in narrow, deep valleys with their sources in narrow ravines trenching the edge of a sandstone capped escarpment. Elevations range from 4,780 feet above sea level on the divide between Armells and Sarpy Creeks down to 2,511 feet at the east line of T6N R41E.

Lithology

In sequence from surface units down to lowermost thick coal-bearing units.

Rock Unit	Thickness	Description
Alluvium	0 - 50'	Channel deposits and terrace gravel.
Terrace gravel	60'	Terrace gravel cemented into a conglomerate; largely made up of andesitic porphry. 1000 to 1,100' above Yellowstone River.
Tongue River member of the Fort Union formation	1,686'	Mostly sandstone and sandy shale. Several of the sandstones thick and massive. Several coal beds.

Structure

The field lies in a broad shallow syncline pitching gently southeastward. Although affected by a few very shallow folds within the field, the strata is essentially flat lying with dips reaching a maximum of 3 degrees in the northwest corner of the field. Several small normal faults, having maximum throws of 60 feet, occur along the boundary between T3N R40E and T3N R41E.

Seams

The Rosebud coal seam consistently exceeds 20' in thickness throughout its extent. It occurs about 360 feet above the base of the Tongue River member of the Fort Union formation. Its primary occurance is in the southern half of the field where the Tongue River member has not been eroded away. This would amount to about 400 square miles. The coal is of subbituminous rank.

Mining Conditions

A large percentage of the Rosebud coal is strippable. Dips are very low and faulting is not a significant problem. In parts of the field the Rosebud seam is overlain by up to 100 feet of hard massive sandstone.

Water Resouces

The field is drained by tributaries of the Yellowstone River, the largest of which are Sarpy, Armells, and Rosebud Creeks and are normally perennial. The northern edge of the field is bounded by the Yellowstone. Practically all of the streams draining the field have shallow pools of slight surface flows here and there along their courses during the dry season.

Fair water in small amounts can be obtained from the terrace gravel of the Yellowstone River. Springs issue from nearly all of the coal beds in the upper part of the Fort Union formation, particularly the Rosebud seam. Several wells obtain significant water from the massive sandstone overlying the Rosebud bed. The alluvial sands and gravels along the Yellowstone River and its tributaries should also be good sources of groundwater.

Moorhead Field

Location

Located on the Powder River, it consists of all or part of 36 townships - about 1230 square miles - in southeast Montana.

Topography

The eastern one-fifth of the area is a broad expanse of rolling grassland which terminates on the west at an extensive partly forested, intricately dissected plateau upon which are large areas of treeless gently rolling grasslands.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	5 - 25'	Silt, sand, and local lenses of gravel along major streams and their tributaries.
Terrace deposits	5 - 65'	Pebble to boulder size material derived from local clinker, sandstone, metamorphic, and igneous rock.
Wasatch formation	200'	Shale, carbonaceous shale, and thin beds of sandstone which erode to ledges on gentle slopes of softer rock.
Fort Union formation	1800 - 2000'	Upper Tongue River member, 1400-1600', consists of interbedded thick beds of sandstone, sandy shale, shale, carbonaceous shale, and about 30 beds of coal. Lower member, 400', is interbedded shale, silty shale, carbonaceous shale, lenses of sandstone, and a few lenticular coal beds.

Seams

Most of the coal greater than 15 feet in thickness is located in the Anderson seam. The largest occurance of Anderson coal is in the western portion of the field, west of the Powder River. The area underlain by Anderson coal greater than 15 feet thick is 110,504 acres. The Canyon coal bed lies 150 to 300 feet below the Anderson seam and represents about 22,260 acres of coal in excess of 15 feet. The Dietz No. 2 seam lies between the Anderson and the Canyon seams and has an areal extent of 620 acres of 15 foot coal. At 230-280 feet below the Canyon Bed the No. 5 coal bed reaches a thickness 19 feet 4 inches in T9S R47E. Its areal extent is estimated to be 670 acres East of the Powder River. No. 8-9 coal bed exceeds 15 feet at several locations. It's total thickness is estimated to be 15 feet in T8S R49E where its areal extent is estimated to be 2,110 acres. The Canyon No. 3 bed covers about 540 acres in T9S,R51E. All of the above mentioned coals occur in the Fort Union formation with the maximum depth to coal being less than 800 feet and in most places, less than 600 feet.

Mining Conditions

Much of the coal in this field is at shallow depths and therefore most suitable to surface rather than underground mining. Some small local folds are present and some faults are mapped in the exposed rocks. In the southwestern part of the area, several normal faults, which trend generally slightly north of east for distances of up to 7 miles, displace the exposed rocks. Faults, however, are of minor importance in terms of being a hindrance to mining.

Water Resources

The surface water resources of the area are significant. The Powder River has cut a wide valley northeastward across the east margin of the plateau and thence northeastward across the rolling lowland. Its flood plain ranges in width from ½ to 2 miles, and the bed of the river is about 15 feet below the surface of the flood plain. The Little Powder River flows northward across the eastern part of the area entirely in the rolling lowland of the mapped area and joins the Powder River about 4 miles south of the north boundary of the field.

The belts of alluvium along the Powder and Little Powder Rivers have potential as useful sources of groundwater. The Wasatch formation is known to yield water from lenticular sandstone and to a lesser extent from jointed coal and clinker beds. The Fort Union formation yields water from fine-grained sandstone, jointed coal, and clinker beds.

Northward Extension of the Sheridan Field

Location

The field occupies 700 square miles in southeast Montana including parts of Rosebud and Big Horn counties. The southern border is the Montana-Wyoming state line, the western border is the Crow Indian Reservation, the northern border is the Northern Cheyenne Indian Reservation, the eastern border is formed by Hanging Woman Creek, the Tongue River and the eastern side of T8, 9 and 10S R43E.

Topography

The area is characterized by low rolling hills and buttes. Prairie grasses and sage dominate the vegetation, but stands of evergreens are scattered throughout. The Tongue River and its floodplain crosses the field from northeast to southwest and many tributaries enter the river from the northwest and southeast.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace deposits	0 - 50'	Terrace and alluvial silt, sand, and gravel deposits along the course of the Tongue River and its tributaries.
Wasatch formation	500'	Interbedded sandstones, shales, small amounts of sandy limestone, and thin coal.
Tongue River member of the Fort Union formation	up to 1800'	Interbedded claystone, siltstone, sandstone, coal, and clinker. Sandstone commonly occurs in thick beds.

Structure

The field is located in the northern part of the Powder River Basin, a great structural depression between the Big Horn Mountain uplift on the west, and the Black Hills uplift of the east. Dips are chiefly to the southeast veering toward the south and southeast in the southeast corner of the area. Local dips are less than 3 degrees. Minor faults occur throughout the field.

Seams

The Smith, Anderson, Dietz No. 1, Canyon, Wall, Brewster-Arnold, and Knablock beds all exceed 15 feet in thickness in some part of the field. There is some difficulty in correlating beds within the field and with surrounding fields so that locally the names of the beds are in dispute. Suffice it to say that at least seven beds in the field contain coal which exceeds 15 feet in some places. The coal is high grade subbituminous.

Mining Conditions

Low dips are the rule throughout most of the field although dips can range up to 17 degrees adjacent to faults. Faulting is not wide spread or large scale but can be of local significance. Much of the coal in the field is under shallow overburden and is strippable but much is under over 200 feet of overburden giving it potential for underground mining.

Water Resources

Ground water occurs in the alluvium along the stream channels, in the coal seams, in the sandstone units, and in clinker beds. Many bedrock wells are completed in the coal seams and yield adequate supplies of water for livestock and domestic use.

The primary surface streams are the Tongue River and its largest tributary in the area, Hanging Woman Creek. Youngs Creek is perennial and joins the Tongue River about 16 miles upstream from the Tongue River Reservoir. The Tongue River Reservoir is a large irrigation reservoir located in the central portion of the field on the Tongue River and is the most significant body of surface water in the area.

Tullock Creek Field

Location

Located on the east side of the Big Horn River in southeast Montana. Found in the angle formed by the junction of the Big Horn River with the Yellowstone River. Extends eastward to the center of R38E and south to the Crow Indian Reservation boundary. Occupies about 900 square miles.

Topography

Essentially a maturely dissected plateau across which the Yellowstone and Big Horn rivers have cut wide valleys.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - 90'	Coarse gravel, sand, and silt.
Fort Union formation	0 - 675 +	Sandy shale, clay shale, and sandstone in thick layers. Coal beds.

Structure

Located in a broad, shallow syncline crossed by a structural upwarp. In the northern part the strata dip gently to the south, in the southern part they are tilted more steeply to the north and east, and in the central portion they are gently warped and are faulted to some extent. Tilted more steeply in the southwest corner (dips up to 30 degrees) due to the Big Horn uplift.

Seams

The thick seams are the M and P seams (as defined by U.S. Geological Bulletin 749) occuring in the upper portion of the Fort Union formation. Both are lenticular and occur in thicknesses exceeding 15 feet in the southeast corner of the field. The coal is subbituminous in rank.

Mining Conditions

Dips are generally low throughout the field except in local areas primarily in the southwest corner of the field where the Big Horn uplift and the Lake Basin fault zone have resulted in dips up to 30 degrees. Faulting is of minor significance where coal exceeds 15 feet in thickness. The thick coal is lenticular, thinning outward from a central area where it reaches maximum thickness.

Water Resources

The Yellowstone River, Big Horn River, and Tullock Creek all flow through or adjacent to the field. The most likely significant surface water to be affected by thick seam mining however, is Sarpy Creek and its tributary East Sarpy Creek which flow through the southeast corner of the field. In wet years these are perennial streams and contain water in some sections even in dry years.

Groundwater is found in the coal seams themselves, in some of the sandstone layers of the Fort Union formation, and in the alluvium located along the stream channels within the field.

Fruitland - Fruitland Field

Location

Located in the northwestern portion of the San Juan Basin. Bounded on the north by the Colorado-New Mexico state line, on the south by the San Juan River, from west to east between ranges 15W and 12W.

Topography

In the southern part of the field the topography is characterized by broad alluviated flats interrupted by sharp sandstone-capped cuestas with relief varying from a few feet to a few tens of feet. As the dip of the beds increases northward, the surface is marked by narrow ridges and valleys and high, tilted mesas.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - 50'	Stream deposited sand and gravel.
Kirtland shale	0 - ?	Shale with channel deposited Farmington sandstone member near its middle.
Upper portion of Fruitland formation	250'	Sandy shale with sandstone, cross-bedded sandstone, and coal beds.

Structure

The Fruitland - Fruitland field is located on the northwestern edge of the San Juan Basin which is an asymmetrical circular structure deepest to the northeast. Dips are generally in an easterly to southeasterly direction. They increase from 1½ degrees to 3 degrees in the southern part of the field (where the outcrop of the Fruitland formation trends north-south) to 40 degrees near the eastern border of the Ute Mountain Indian Reservation. From there the dips once again decrease to an average of about 9 degrees east of the La Plata River.

Seams

The thick seam is the Carbonero bed of the Fruitland formation. Measured sections and drill holes indicate that thicknesses in excess of 15 feet occur in the extreme northern and southern portions of the outcrop. Average thickness throughout the field is projected at 25 feet. Quality is high-volatile C and B bituminous.

Mining Conditions

In areas of low dips, much of the coal is strippable where overburden depths permit. In areas of deeper overburden and higher dips underground techniques are appropriate. The steeper dips in some areas may be a hindrance to mining. Some minor faulting should be expected in the vicinity of flexures but faults are not an obvious problem on the surface.

Water Resources

Within the area defined as the Fruitland - Fruitland Field are located portions of two perennial streams, the La Plata River and the San Juan River. Both of these streams can be considered to be of significant economic and ecological importance.

The field does not contain any aquifers of major regional importance but the sandstone members and coal beds of the Fruitland and Kirtland formations can be considered to be locally significant sources of groundwater.

Blacktail (Tabby) Mountain Field

Location

Located in Wasatch County on the south flank and near the west end of the Uinta Mountains. The field occupies an area of about 150 square miles.

Topography

For the most part the surface is rugged. Elevations range from 6,400 feet to 10,600 feet at the summit of Blacktail Mountain. The central portion of the field is dominated by Blacktail Mountain and the Red Creek and Farm Creek peaks. The slopes of these higher areas are dissected by small valleys. Generally however, the surface consists of hogbacks produced by the unequal erosion of upturned strata. Valleys between the hogbacks are occupied by smaller streams but the larger streams flow across the upturned edges of the strata.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - 50'	Sand, gravel, and clay along streams.
Terrace gravel	0 - 20'	Sand and gravel 200 - 300' above valley floors.
Glacial material	0 - 50'	Sand, clay, pebbles, and boulders unstratified and deposited as terminal, lateral, and recessional moraines.
Bishop conglomerate	0 - 500'	Conglomerate composed of waterworn and subangular quartzitic pebbles and boulders, many 1 to 6 feet in diameter, embedded in finer sand and gravel.
Bridger and Uinta formations	0 - 600'	Course massive sandstone alternating with thin beds of sandy shales.
Green River formation	0 - 2000'	Sandy shale with thin beds of sandstone.

Wasatch formation	10,000' ±	Sandstone, sandy shale and conglomerate, poorly consolidated.
Mesaverde formation	0 - 1650'±	Alternating beds of sandstone, shale and coal.

Structure

The field occupies a portion of the northern margin of the Uinta basin where strata have been upturned along the south flank of the Uinta Mountains. Dips are therefore generally high, ranging from 20 to as high as 57 degrees. Strikes run approximately east-west in the most of the field with dips toward the south away from the mountains on the north.

Seams

The thick seam is located within the Mesaverde formation and is designated the Fraughton bed in U.S. Geological Survey Bulletin 471. The Fraughton bed is exposed in T1S R9W along Red Creek for a distance of about 2 miles. Another exposure about 5 miles to the west in T1S R10W is about 20 feet in thickness and is possibly an extension of the Fraughton bed although positive correlation has not been made. The beds dip to the south at up to 45 degrees and the persistance of the Fraughton seam in the subsurface is unknown.

Mining Conditions

The high dips present in the field are the most obvious obstacles to mining. No significant faulting is present at the surface in the field although localized faulting in the subsurface would not be unexpected given the deformed nature of the upturned beds.

Water Resources

The Duchesne River is the principal stream in the area and flows southeasterly across the field a short distance east of its center. Currant, Red, and Rock creeks have courses similar in direction to that of the Duchesne. These are all perennial streams. The discharge of the Duchesne at Myton, Utah in 1908 was measured at 143,000 acre-feet in June and 32,100 acre-feet in September.

The glacial material in the field is known to be water bearing and the terrace gravels and alluvium along the stream channels also have potential as groundwater sources. The Bishop conglomerate is a good water bearing formation and supplies many of the springs in the field. The Bridger and Uinta formations as well as the Mesaverde formation also contain water in significant amounts.

Book Cliffs Field

Location

The field lies slightly east of the central part of Utah. The west end of the field is about 120 miles southeast of Salt Lake City. The east boundary is the Green River, the west boundary is the eastern most fault of the North Gordon fault zone, the south or southwest boundary is the escarpment of the Book Cliffs, and the north-northeast boundary is somewhat beyond the 3000 foot overburden line.

Topography

The most important topographic features of the Book Cliffs coal field are the Book Cliffs themselves. The 70-mile cliff line extends along the entire length of the field on its south side. Relief along the cliffs varies between 1000 and 2000 feet. Behind the cliffs are mountains with more gentle slopes and in the north and west part of the field locally flat surfaces have been developed along the Flagstaff limestone - Colton formation contact. The coal outcrops along the cliffs and in the canyons which indent them.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Unit	Thickness	Description
Green River formation	Full thickness unknown	Claystone, shale, and fine-grained thin bedded sandstone.
Colton formation	300 - 2000'	Lenticular sandstone, shale, and siltstone.
Flagstaff formation	0 - 500'	Limestones, shales, and fine-grained calcareous sandstone.
Wasatch formation	3000'	Found in the eastern portions of the field and is equivalent to the Colton and the Flagstaff in the west. Sandstone with shales and a basal conglomerate.

North Horn formation	350 - 2500'	Calcareous and silty shale, fine-grained sandstone and minor conglomerate.
Tuscher formation	0 - 200'	Only present in east part of field and probably represents lower part of North Horn. Friable massive sandstone and subordinate gray shale.
Price River formation	500 - 1500'	Medium-grained sandstone and shaley sandstone with some shale.
Castlegate formation	100 - 500'	Fine to medium-grained, argillaceous, massive resistant sandstone with subordinate shale.
Blackhawk formation	600 - 1000'	Cyclical littoral and lagoonal deposits with six major cycles. Littoral deposits are mainly thick bedded to massive, cliff-forming fine to medium-grained sandstone with individual beds separated by gray shale. The lagoonal facies include thin to thick-bedded sandstones, shaley sandstones, shale, and coal. Castlegate coal zone occurs about 700 - 900 feet down from contact with Castlegate sandstone. Lower Sunnyside coal bed is located 200 - 300 feet below Castlegate sandstone contact.

Structure

The Book Cliffs roughly parallel the strike of a homocline dipping into the Uinta Basin to the northeast. Faulting is generally local and of minor displacement. The most serious group of faults lies in the southern portion of the field where two steeply dipping fault sets occur; the first trends north-northwest, the second east-northeast. Although they can be a hindrance to mining, they are fortunately not too closely spaced. Dips for the strata in the field are generally low, ranging from 1 or 2 degrees to 10 or 12 degrees.

Seams

Two coal seams exhibit thicknesses greater than or equal to 15 feet in the Book Cliffs Coal Field. The Lower Sunnyside bed has thickness greater than 15 feet in its southern most portion at the Geneva and Book Cliffs mines. Thicknesses in areas of 2000 feet or more of overburden are unknown. The Castlegate zone includes the Castlegate "A" and "D" beds, both of which have thicknesses exceeding 15 feet in the areas where they outcrop. Both the Lower Sunnyside bed and the Castlegate beds occur in the Upper Cretaceous Blackhawk formation. The coal in all of these beds is classified as high volatile B bituminous.

Mining Conditions

Mining conditions are generally good. Beds are locally continuous and are cut by only a few widespread faults. Dips on the beds average between 5 and 7 degrees. The seams do contain floor and roof undulations and thickness changes characteristic of western coal seams. In some places the coal has been removed by prehistoric erosion events or splits of shale or high-ash coal appear and disappear.

Water Resources

The most likely candidates as significant sources of groundwater are the Flagstaff limestone, the sandstone and conglomerate units in the North Horn formation, the Price River and Castlegate sandstones and sandstone and coal units of the Blackhawk formation. Given the low amounts of precipitation and small recharge areas, these resources are somewhat limited however.

Surface water is of more importance for the Book Cliffs field than is groundwater. Two important streams, the Price River and the Green River, flow through the cliffs at opposite ends of the field. The Price cuts through at both ends while the Green skirts the field at its extreme southern end where it is joined by the Price.

The Price River in the vicinity of Helper is most likely to feel the effects of underground coal mining. During the water years 1914 to 1934, it had an average annual flow of 138 cfs. Coal Creek, Soldier Creek, Dugout Creek and Whitmore Creek usually have a small but sustained flow. Chemically, surface waters above the cliffs are low in dissolved material, usually between 300 and 500 ppm, the concentration found in the Green River in this area. Below the cliffs the water passes over the Mancos Shale and is used for irrigation, both of which help increase the dissolved material to more than 1200 ppm.

Kaiparowits Plateau Field

Location

Located in south central Utah. The plateau has a maximum width of 54 miles at its south end and is 66 miles from north to south. Its eastern boundary is defined by the Cretaceous Dakota formation which outcrops along the Straight Cliffs (Fiftymile Mountain). On the north, the base of the overlapping Tertiary strata of the Table Cliff and Aquarius plateaus represents its boundary. On the south the field is bounded by the base of the Dakota outcrops along the deep canyons of the Colorado River system and on the west by the Paunsaugunt fault and the base of the Dakota Formation as it outcrops along the East Kaibab monocline.

Topography

The Kaiparowits area is one of undulating plateau surfaces deeply incised by steep-walled canyons along the walls of which are exposed the coal seams. Elevations range from 3,800 to 8,000 feet above sea level and the coal seams occur throughout the entire range of elevations. The highest elevations are in the north part of the field and the lowest are along the Dakota outcrops in the south end of the field.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Surficial deposits	0-200'	Alluvial and colluvial sands and gravels, landslides, sand dunes and sheets, pediment gravels, terrace deposits, and, in extreme north, 200' of volcanic latite flows.
Clarion formation	0-1500'	Upper member a varigated siltstone, mudstone and sandstone. Middle member 0 - 550' of white limestone. Lower member 0 - 900' of pink limestone.

Canaan Peak	0 - 900'	A 0 - 400' thick mudstone and bentonic claystone above a 0 - 500' interbedded sandstone, conglomeratic sandstone, and conglomerate.
Kaiparowits formation	2000 - 2500'	Fine to moderately course-grained friable arkosic sandstone with subordinate mudstone units up to 10' thick and lenses and irregular beds of sandy limestone.
Waheap formation	760 - 1350'	Resistant sandstone, gritstone, and conglomerate alternating with non-resistant sandstone and mudstone. Lower half predominantly non-resistant, upper half massive and hard.
Straight Cliffs formation	600 - 1450'	Drip Tank member, 100-550' is a cliff former of fine to medium-grained sandstone with some gritstone and conglomerate interbedded with shale. John Henry member, 500-900', contains thick coal and interbedded medium-grained sandstone, shale, and carbonaceous mudstone.

Structure

The Kaiparowits Plateau can be characterized as a basin with a system of asymmetrical anticline-syncline sets usually trending northwest and plunging into the central basin. Relatively few faults occur within the plateau and they are of minimal importance in terms of their effects upon mining conditions. Many of the faults are surficial with small extent and depth and are the result of collapse at the edge of oversteepened canyons or above portions of burned coal seams. The presence of synclines, anticlines, and monoclines creates variations in dip throughout the plateau.

Seams

The John Henry member of the Cretaceous Straight Cliffs formation contains all of the significant coal zones of the Kaiparowits field. In terms of seams greater than 15 feet in thickness, the Alvey and the Christensen zones are of the most importance. The Christensen zone is projected throughout most of the field while the Alvey zone has only been confirmed for the eastern half of the field. Most of the Christensen zone outcrops appear along the walls or at the bottom of deep canyons necessitating the use of underground mining techniques. The Alvey zone occurs about 300 to 400 feet above the Christensen and it too requires exploitation by deep mining. The seams of both zones tend to be lenticular so that the thick seams can be expected to occur only at specific localities rather than extending throughout the field. The rank of the coal in the Kaiparowits field ranges from subbituminous C to high-volatile bituminous A.

Mining Conditions

The geology of the Kaiparowits Plateau dictates that most coal seams will have to be mined underground. The coal beds tend to be lenticular creating problems in adjusting mining equipment to conform to seam thickness. Faulting is of limited extent and in general should present only minimal problems for mining except locally along the limbs of some folds where they can increase up to about 65 degrees.

Water Resources

Streams occuring on the plateau itself are mainly dry except in the north. The largest amounts of significant surface water in the area are adjacent to the plateau in the north and south. The Escalante River flows northeast of the plateau and and has an average annual flow rate of 3,500 acre-feet near the town of Escalante. To the south is Lake Powell into which the Colorado River normally discharges more than 7 million acre-feet of water. Those creeks heading on the plateau and which add to the flow of the Escalante have a total annual discharge of about 8000 acre-feet which is used for irrigation and domestic purposes by the communities in Escalante Valley. The Paria River on the southwest limits of the plateau is estimated to have an annual flow of a little less than 3,500 acre-feet. In the central part of the plateau many drainages confined by the structure empty southward into the Colorado River. These are usually dry except during periods of heavy rain. Many small "water keeps" are constructed by the ranchers to control flash floods and provide water for stock.

Underground aquifers are thought to be potential sources of water for the Kaiparowits Plateau because of the closed basin structure existing on it. Unfortunately little data is available. Some water may be available in the Wahweap and Straight Cliffs formations, but the lenticular nature of the strata will probably limit the amount.

Wasatch Plateau Field

Location

Located near the geographical center of Utah. Width ranges from 7 to 20 miles, length about 90 miles. Oriented nearly north-south. An erosional escarpment marks the east boundary; the west boundary roughly follows the drainage divide of the Wasatch Plateau. U.S. highway 50-6 or the main line of the Denver and Rio Grande Western Railroad designates the north boundary. To the south the field terminates against the volcanics of the Fish Lake Plateau.

Topography

The plateau is made up of rugged topography with ledges and steep slopes. The eastern edge is marked by a steep cliff with a relief of about 1000 feet and cut by deep canyons. Coal is exposed in the canyon walls and along cliffs. Exploitation usually has taken place in areas of good accessibility such as where tributary canyons V into the cliffs. Altitudes range from almost 7000 to more than 10,000 feet above sea level. Coal outcrops mostly between 7000 and 8000 feet.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Green River formation	0 - ?	Shale and siltstone with some lenticular sandstones. Found in northern part of plateau.
Colton formation	300 - 1500'	Varicolored shale with limestone and sandstone lenses.
Flagstaff limestone	200 - 1500'	Limestone evenly bedded with minor amounts of sandstone, shale, and volcanic ash.
North Horn formation	500 - 2500'	Variegated shales with subordinate sandstone conglomerate and limestone. Thickens to the north.

Price River formation	600 - 1000'	Gritty sandstone interbedded with subordinate shale and conglomerate.
Castlegate sandstone	150 - 500'	Coarse-grained often conglomerate sandstone.
Blackhawk formation	850'	Fine to medium-grained sandstone interbedded with subordinate shale and conglomerate. Coal beds are in the lower 250 to 350 feet. Aberdeen sandstone member underlies the Castlegate "A" bed.

Structure

Except adjacent to fault zones the beds usually dip at low angles up to 5 or 6 degrees. Locally in and around fault zones dips may reach 20 degrees. Direction of dips is generally westerly except in the extreme north part of the field where it is northerly. The faults tend to impede or limit mining but there is usually ample room between faults to mine profitably.

Seams

All the coal resources of the Wasatch Plateau are contained in the lower third of the Blackhawk formation of the Mesaverd group (Upper Cretaceous). The Hiawatha, Castlegate "A", Bear Canyon, Blind Canyon, Candland and Muddy No. 2 beds all equal or exceed 15 feet in thickness for some part of their extent. Of these, the Hiawatha and Castlegate "A" are considered to be of most importance. The Hiawatha rests immediately upon the Star Point sandstone and has the greatest areal extent. The Hiawatha is best developed in the Hiawatha area where beds up to 28 feet thick have been mined. The Castlegate "A" is located from 160 to 210 feet above the Star Point sandstone and is up to 19 feet thick. The coal in all the beds of the Wasatch Plateau is high volatile B bituminous.

Mining Conditions

A series of fault zones generally trending north-south cut and displace the coal. The faults tend to increase the dips in the strata adjacent to them and to limit mining in some areas by creating discontinuities through offsetting of the coal beds. Locally extensive shearing and crushing along the fault plane reduces the volume of minable coal. Faults are also avenues for underground water in places dewatering the rock and in others channeling water into the mine. The King Mine of U.S. Fuel contains many islands of rock (wants) replacing portions of coal seams which reduce coal recovery. In some areas thicker coal seams come close together thus rendering some seams unminable by conventional techniques. Variable dip, fluctuating thickness of the coal seam and undulating coal require frequent changes in mining plans to accomodate mining machinery and to solve problems of ventilating and dewatering the mine.

Water Resources

The Flagstaff limestone yields water to many springs in the Wasatch Plateau. Individual springs in the Flagstaff have yielded up to 1,900 gpm. Dissolved minerals range from 290 to 428 ppm. The North Horn formation yields water from its sandstone, conglomerate and limestone layers. It contains from 256 to 562 ppm dissolved solids and one spring has produced up to 1800 gpm. The Price River and Castlegate sandstones yield fresh water in several springs with flows up to 25 gpm and dissolved solids from 238 to 303 ppm. Wells have encountered good water in the Blackhawk formation in some places. Dissolved solids range from 245 to 903 ppm and a coal mine west of the Wasatch Plateau intercepted water flowing at 1600 gpm.

The larger streams of consequence on the plateau are the Price River, Huntington Creek, Cottonwood Creek, Ferron Creek, Muddy Creek, Quitchupah Creek and Ivie Creek. The streams are normally permanent. From water years 1939 to 1957 the Price River at a point just above Scofield Reservoir discharges an average of 47.52 cfs. The average flow rate for Huntington Creek near Huntington over a period of 42 years was 98.63 cfs. Near Orangeville Cottonwood Creek averaged 104.1 cfs over a 40 year period. In 22 years of measurement Ferron Creek near Ferron averaged an annual flow rate of 72.6 cfs and in 11 years of record Muddy Creek had an average annual flow of 41.1 cfs near Emery. Based on drainage area the flow rates for Quitchupah and Ivie Creeks should average annually about 60 cfs. Thewater for all creeks in the area of the Wasatch Plateau has a low dissolved solids content ranging between 10 and 300 ppm.

Buffalo - Lake De Smet Field

Location

The field includes parts of Johnson and Sheridan Counties in northcentral Wyoming. Bounded on the north by the Sheridan coal field, on the east by the Barber coal field, on the south by the southern edge of T50N, Rs. 80 to 83 W, and on the west by the Precambrian core of the Bighorn range.

Topography

The field includes parts of two physiographic regions, the eastern slope of the Bighorn Mountains and the Western part of the Great Plains. From the steep pine-covered slope of the eastern flank of the Bighorn Mountains the elevation drops abruptly two to three thousand feet to an area of rounded hills and broad flat-topped benches and terraces. Several high spurs extend eastward into the field several hundred feet above the adjacent country. The foothills topography merges gradually into the plains of the Powder River Basin where the surface is broken by many steep-sided, even-topped ridges which are locally dissected by erosion. Elevations range from about 4,100 to 8,500 feet.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace deposits	0 - 50'	Unconsolidated silt, sand, and gravel in stream channel flood plains, terraces, and pediments.
White River formation	0 - 150'	Conglomerate, coarse-grained arkosic sandstone, sandy clay.
Wasatch formation	1000 - 2000'	Sandstone, shale, carbonaceous shale, and coal grading westward into conglomerate. Upper Moncrief member (0 - 1400') contains cobbles and pebbles of Precambrian rocks. Lower Kingsbury conglomerate member (200 - 800') contains pebbles and cobbles of Paleozoic limestone and dolomite.

Structure

Coal-bearing strata generally have low dips (0 - 5 degrees) toward the east except as they approach the Bighorn Mountain uplift on the west where dips reach 20 degrees or more to the east. Gentle undulating folds occur in the Wasatch formation trending about north 30 degrees west through Buffalo, Wyoming and Lake De Smet. Maximum structural relief is about 200 feet. Another series of north 30 degrees west trending folds lies in the central part of the area and a group of low anticlines and synclines trend north 60 degrees east across the south-eastern part of the area.

Seams

The Monument Peak and Healy beds contain significant amounts of coal in excess of fifteen feet thick. The Monument Peak bed contains 19 feet 6 inches of coal with several thin shale partings in the SE ¼, section 26, T53N, R82W and 16 feet of coal near an abandoned mine about one-half mile to the southwest. The Healy bed is by far the most significant thick seam in the field. At one locality in T51N, R80W the bed is 29 feet thick, it contains 29 feet 6 inches of coal in the Kreselok mine in section 2, T53N, R82W, a core hole on the east side of Lake De Smet penetrated 53 feet of coal, and a hole drilled in section 31 of T52N, R80W penetrated 46 feet of coal. Near the south end of Lake De Smet, the Healy bed is 27 feet thick in SE ¼, section 23, T52N, R82W, and thickens to 112 feet one mile to the west. Another bed tentatively correlated with the Healy (U.S. Geological Survey Bulletin 1078) underlies an area at least 1 mile wide and 2½ miles long in the northeastern part of T52N, R83W, and adjoining parts of the townships to the north and east, and may average more than 100 feet thick.

Mining Conditions

Dips are generally low (less than 5 degrees) except near the Bighorn Mountains. Faulting is minimal. A northeastward-trending normal fault extends for about a mile with a maximum displacement of about 50 feet in the south-central part of T50N, R80W. Drill hole data suggests the existance of a high-angle fault at the northern end of Lake De Smet. Strata on the west side of the fault are dropped about 30 to 150 feet relative to the east side. Much of the thick coal underlies strippable thicknesses of overburden but the beds which outcrop on ridges between tributaries of larger streams and pass under thick overburden a short distance back can best be mined underground.

Water Resources

There are three perennial streams in the field, Crazy Woman Creek, Clear Creek, and Piney Creek, a fork of Clear Creek. All other streams are intermittant. The water in Crazy Woman Creek is somewhat alkaline but that of Piney and Clear creeks is remarkably pure. Lake De Smet is a body of water about 3 miles in length by a mile in width in the western part of T52N, R82W.

Local springs flow from outcropping coal beds along stream channels and in valley bottoms. The sands and gravels in the alluvium and terrace deposits can also be expected to yield some water.

Gillette Field

Location

The field is located in the vicinity of Gillette, Wyoming in the Powder River structural basin. The field embraces Tps. 39 to 42 N, Rs. 66 to 74 W; Tps. 43 to 47N, Rs. 66 to 72 W; Tps. 48 to 50N, Rs. 66 to 69 W; and most of Tps. 49 to 50N, Rs. 70 to 72 W.

Topography

The field lies in the Northern Great Plains. A 300 to 400 foot high escarpment divides the field from north to south. The escarpment is referred to as Rochelle Hills and is eastward facing, irregular, and locally eroded into badlands. East of the escarpment the surface is a broken plain dissected by narrow stream channels; west of it the surface is a rolling grass-covered prairie in which a few prominent buttes rise about 100 feet above the general level. Total relief in the field is about 1000 feet.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace deposits	0 - 40'	Silt, sand, and gravel deposited along stream channels and in terraces above channels.
Wasatch formation	500-1000'	Soft shales, thin sandstones, and coal beds.
Tongue River member of the Fort Union formation	250-400'	Sandy shale and thin sandstone beds with thick and thin coal beds.

Structure

The structure of the field is relatively simple. Most of the strata have low dips except in the northeast corner of the field where dips increase as the Black Hills uplift is approached. Dips are generally toward the southwest or the west away from the

Black Hills. Some minor flexures are present, notably in Tps. 45 and 46N, R70W and near Minturn.

Seams

The Felix, Anderson, Canyon, and Wyodak seams are the primary thick coal seams in the field. The Felix occurs in the Wasatch formation and locally reaches thicknesses of 50 feet. The Anderson and Canyon seams exceed 15 feet throughout much of their extent and coalesce in the eastern portion of the field into the Wyodak seam. This seam is known to exceed thicknesses of 100 feet over large areas. The Anderson, Canyon, and Wyodak seams are found in the Tongue River member of the Fort Union formation.

Mining Conditions

Dips are generally low throughout the field with some local increases or direction changes. In the northeast portion of the field dips increase towards the Black Hills uplift. Much thick coal is available to surface mining as is evidenced by a number of strip mines operating within the field. Towards the western portion of the field overburden depths increase beyond the present 200 to 250 feet limit observed for strip mining.

Water Resources

Except for a few square miles in the northwest corner of the field, the field lies almost completely within the drainage basins of the South Fork of the Cheyenne River and the Belle Fourche River. All three streams carry little or no water during the summer months.

Springs and wells produce water from the sandstone and coal units of the Wasatch and Fort Union formations as well as from alluvium along river channels. The coal units can probably be considered the most reliable sources of reasonably good quality groundwater.

Kemmerer Field

Located in the southwest corner of Wyoming in Lincoln and Uinta counties. The Kemmerer field is elongated in a north-south direction as far north as T23N and as far south as the Utah-Wyoming state line. It is approximately bounded on the east by the Meridian anticline and on the west by the Absaroka fault.

Topography

The Kemmerer field is characterized by a series of north-south trending hogbacks developed on the edges of upturned strata of varying erodibility. Elevations on the hogbacks range from 7000 to 8000 feet above sea level. The field is bordered on the west by the Absaroka Ridge and on the east by the Meridian Ridge. In the central portion of the field is found the Mammoth Ridge, a broad flat plain running north-south for most of its length.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and colluvium	0 - 300'	Terrace, floodplain and hillwash deposits ranging from clay through gravel.
Wyoming conglomerate	0 - 50'	Pebbles in a light-gray sandstone matrix.
Bridger formation	1800'	Greenish sands and clays.
Green River formation	2000'	Thin-bedded shales.
Wasatch group	+1500'	Sandy clays with irregularly bedded sandstones.
	+2500'	Beds composed largely of volcanic ash but containing thin limestone layers.

	2100'	Conglomerate sandstones, and sandy clays.
Adaville formation	+5000'	Gray and brown clays with irregularly bedded brown sandstone and numerous coal beds. At base is 100 to 200 foot thick Lazeart Sandstone. Immediately above this is the Adaville - Lazeart coal.

Structure

The structure of this field is extremely complex owing primarily to deformations taking place in the late Cretaceous. The Cretaceous activity resulted in, from east to west: (1) a rather irregular anticline - the Meridian anticline; (2) a somewhat disturbed, and in places overturned syncline - the Lazeart syncline; (3) a much broken region lying between this syncline and the fault to the west; (4) a large and very persistant faulted anticline, with a downthrow to the east-the Absaroka fault. The thick coal seams lie in the Lazeart syncline whose axis runs generally north-south. Rocks of Upper Cretaceous age have been down folded into the trough. The east limb of the syncline forms prominent parallel hogback ridges. Strata of the east limb dip 16 to 23 degrees to the west, and the west limb dips steeply to the east.

Seams

A number of seams exceeding 15 feet in thickness occur in the Adaville formation. One cross-section across the northern part of the field exposes five such beds. The maximum thickness for a single bed is 100 feet for the No. 1 Adaville seam 2 miles north of the Elkol mine in T20N R117W. The coal ranges in rank from high grade subbituminous to high grade bituminous.

Mining Conditions

Conditions in this field are more conducive to underground versus strip mining although steep dips as well as variations in dip could be a hindrance to longwall mining. The structural complexity of the area contributes to the possibility that thickening, thinning, and offsetting of beds could disrupt the mining process. The coals of the region tend to be highly variable in thickness as a result of splitting and coalescing.

Water Resources

The alluvial sand and gravel deposits of stream floodplains and terraces offer potential as sources of ground water. The sandstones and conglomerates of the Wasatch formation have yielded flowing water in several wells ranging from brackish to good quality. The downwarped nature of the strata of the field creates significant recharge of areas along the eroded edges of permeable beds so that they become potential sources of groundwater within the synclinal basin.

Ham's Fork flowing through the northern portion of the area is the most significant body of surface water in the field. A number of smaller streams and tributaries, some perrenial, have potential for disruption from the subsidence effects of underground coal mining. These include Albert Creek, Muddy Creek, and Little Muddy Creek.

Little Powder River Field

Location

The field is located about midway between the Black Hills and the Bighorn Mountains. It occupies an area 15 miles wide on the west side of the Little Powder River extending southward about 35 miles from the Montana-Wyoming state line.

Topography

The field is made up of an intricately dissected level plain in which the average relief is from 300 to 400 feet. The larger valleys are broad with streams meandering through alluvium-filled bottoms. The smaller drainage channels are sharply cut and have a badlands appearance with narrow ridges and steep-sided gullies.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - ?	Silt, sand, and gravel deposits found along stream channels.
Tongue River member of the Fort Union formation	2000' +	Interbedded sandstone, shale, and coal. Sandstone often found in massive, thick beds.

Structure

The strata is nearly horizontal except where folded locally into flat, shallow synclines and anticlines, few of which are more than 100 feet in altitude from crest to trough. General dip of the strata is less than 1 degree west in the southwest part of the field but to the east dip gradually increases toward the Black Hills uplift.

Seams

The Roland, Smith, and F coal beds (as designated by U.S. Geological Survey Bulletin 471) all exceed 15 feet in thickness in some parts of the field. Occurrances of the Smith and F beds is confined primarily to the northern half of the field. The Roland bed outcrops throughout the north-south length of the field along its western edge.

Mining Conditions

Much of the coal is strippable due to low dips and shallow overburden. Overburden becomes deeper toward the western edge of the field. Faulting is minor and should not be a hindrance to mining.

Water Resources

The main streams are the Little Powder River, Wildcat, Horse, Elk, Olmstead, and Bitter creeks. These streams all normally have small flows during the summer but can become dry at times.

Springs are common during the average summer season, particularly around the edges of clinker outcrops. In addition ground water is contained in the alluvium along stream channels and in the sandstone and coal beds of the Fort Union formation.

Powder River Field

Location

The field occupies about 1000 square miles in Campbell, Johnson, and Sheridan Counties, Wyoming. It is shaped like an hourglass and trends generally northwest. It includes the town of Gillette, Wyoming and overlaps part of the Gillette field.

Topography

The field lies in the Great Plains province between the Bighorn Mountains and the Black Hills. Much of it is deeply dissected badlands topography. From high points in these areas can be viewed steep-sided ridges, buttes domes, and precipitous bluffs. Other areas are of more gentle topography and are grass covered. Altitudes range from 3600 feet above sea level to about 4,900 feet.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace deposits	0 - 40'	Silt, sand, and gravel deposited along stream channels and in terraces above channels.
Wasatch formation	500 - 1600'	Soft shales, thin sandstones, and coal beds.
Tongue River member of the Fort Union formation	250 - 2000'	Sandy shale and thin sandstone beds with thick and thin coal beds.

Structure

The field is part of the Powder River structural basin. The structure is relatively simple with strata essentially flat-lying except where the uplifts such as the Black Hills and the Bighorn Mountains are approached. The average dip of the beds in the southwestern part of the field is about 2 degrees west. The westward dip near Gillette strikes nearly north and south and brings the coals of the Tongue River member to the surface.

This slight monocline determines the eastern edge of the field. Minor warpings and faults occur throughout the field.

Seams

The Gillette field contains a large number of coal seams which exceed 15 feet in thickness. The Felix bed occurs in the Wasatch formation and locally reaches thicknesses in excess of 50 feet. The Anderson, Dietz, Canyon, Cook, Wall, Upper Pawnee, and Cache beds occur in the Tongue River member of the Fort Union formation. The Anderson and the Canyon coalesce in the eastern part of the field to form the Wyodak which reaches thicknesses in excess of 100 feet east of Gillette. In the eastern portion of the field much of the thick coal is surface mineable. In the western part of the field the coals of the Tongue River member are covered by deeper overburden including thicknesses of the overlying Wasatch formation.

Mining Conditions

Dips are generally low, faulting is minimal, and the thick seams often have good continuity over large areas. In the eastern portion of the field much of the thick coal, particularly the Wyodak seam, is under shallow overburden and is mineable by surface methods. In the western portion of the field thick coal is found under overburden thicknesses which preclude surface mining.

Water Resources

Significant surface water resources are found in this field. The largest stream is the Powder River, found in the northwestern portion of the field. Other streams include the Little Powder River, Rawhide Creek and Crazy Woman Creek.

Groundwater can be found in most of the coal seams and these are often used as domestic water supplies. Sandstone units within the Wasatch and the Tongue River member may also locally supply usable quantities of water.

Rock Springs Field

Location

The field is located in the southern part of Wyoming, in the central portion of Sweetwater County. The south end of the field is only a few miles north of the Wyoming-Colorado state line. It occupies the crest of a low structural dome and the outcrop of the coal-bearing rocks around the edge of the dome gives the field a natural boundary.

Topography

Resistant sandstone layers make notable concentric ridge or hills that are more or less continuous about the central portion of the dome. The ridges are separated from each other by belts of low relief. Shale in the central portion of the dome results in low relief there. The hard, resistant limestone and sandstone beds of the Green River and Wasatch formations produce table-like forms bounded by prominent escarpments and in places produce benches in regular succession bounded by nearly parallel valleys. In parts of the field the beds present characteristic badlands topography. Sand dunes are a conspicuous feature in the northern part of the field. The soft beds of the Wasatch form low depressions along the synclinal trough of the Great Divide Basin and along Killpecker Valley. Few of the Wasatch coal beds are well exposed so that their presence can often only be inferred. The topography however, allows easy access to the coal beds. The hills covered by the Bishop conglomerate have long, gentle, grass-covered slopes. The extrusive igneous rocks of the Red Desert area form nearly concentric cones, needle-like necks, irregular dikes, and table-like sheets.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - 25'	Silt, sand, and gravel deposits along stream channels.
Leucite lava	0 - 350'	Dikes, flows, volcanic necks, and agglomerate.
Bishop conglomerate	0 - 200'	Pebbles and boulders up to 6 feet in diameter embedded in finer sand and gravel.
Green River formation	0 - 630'	Massive sandstone, shaly sandstone, some limestone, and shale.

	0 - 950'	Thin-bedded shale, sandstone, and limestone.
	0 - 800'	Clay, shale, and sandstone, in places slightly conglomeratic.
Wasatch formation	100 - 275'	Thin fissile shale and sandstone, oolitic limestone in places 20 to 50' thick near base.
	1000 - 3500'	Alternating layers of sandstone, carbonaceous shale, coal beds, and conglomerate. Basal sandstone is conglomeratic.

Structure

Structure consists of a huge dome of Cretaceous and Tertiary rocks which rise in the midst of the nearly horizontal rocks of the Green River basin. The major north-south axis of the dome is about 90 miles long. The beds along the west limb dip from 5 to 30 degrees east. The east-west axis of the dome is about 50 miles long. The Black Rock coal group outcrops more or less concentrically around the dome. The dome contains many normal faults of considerable throw. Horizontal displacement can be up to 3 miles while vertical movement is generally less than 100 feet although in a few localities it is several times that.

Seams

The Black Rock coal group contains the thick seams in the field. Although it is included as the lowest member of the Wasatch formation in this area, it is thought to be of an age equivalent to the Fort Union formation in surrounding areas. The Black Rock coal group outcrops in concentric b~~o~~ands around the perimeter of the fields structural dome. At Table Rock a Union Pacific well records a Black Rock coal seam 15 feet thick. One bed in the Black Rock group is known to reach a thickness of 25 feet (NW ¼, SW ¼, section 34, T21N, R100W). Generally the Black Rock coal slopes away from the central dome and persists into areas of thicker overburden, particularly towards the east, southeast, and south.

Mining Conditions

The continuity of the thick seams is unknown but it's likely that they vary considerably in thickness. Slopes generally are of a minimum of 5 degrees but may be as high as 30 degrees. The field is complicated by extensive faulting which may or may not create problems for mining depending upon the locality. The amount of faulting decreases with distance from the center of the dome. Because of the structure within the field and generally medium to deep overburden, underground mining would seem most appropriate.

Water Resources

The most prominent stream in the field is Bitter Creek. It flows across the central portion of the dome at nearly right angles to the major axis through a broad valley. The three largest tributaries of Bitter Creek are Killpecker, Little Bitter, and Salt Wells creeks. The entire region is a desert and none of the streams can be considered to be good sources of water.

In the southern part of the field the Bishop conglomerate supplies many springs. The sandstones and coal beds of the Wasatch formation are possible sources of groundwater but potential recharge is minimal. The alluvial sands and gravels along the stream channels may also produce some water.

Sheridan Field

Location

The Sheridan coal field is located in northeastern Wyoming, east of and near the Bighorn Mountains. The northern boundary is the Wyoming-Montana state line. Its eastern boundary is the eastern edge of R79W, it extends no further south than the southern edge T54N and no further west than the western edge of R85W.

Topography

The field occurs on the western edge of the broad plain that extends from the Bighorn Mountains to the Black Hills, part of the Powder River structural basin. Highlands consist of crests of major watersheds and higher ridges between the principle valleys. Highlands undulate between levels of nearly 4,200 feet in the east to 4,600 feet at the approach to the foothills of the Bighorn Mountains. Here and there stream headwaters reduce highlands to zigzag sharpcrested ridges intersected in places by shallow gaps. The lowest elevation is 3,400 feet in the Tongue River at the state line.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium and terrace gravels	0 - 50'	Terrace and alluvial silt, sand, and gravel deposits along the course of the Tongue River and its tributaries.
Wasatch formation	500'	Interbedded sandstones, shales, small amounts of sandy limestone, and thin coal.
Tongue River member of the Fort Union formation	up to 1800'	Interbedded claystone, siltstone, sandstone, coal, and clinker. Sandstone commonly occurs in thick beds.

Structure

The field is part of the Powder River structural basin and represents a portion of a wide, flat trough or basin between the Black Hills and the Bighorn Mountains. Dips are generally low and to the southeast but may be locally higher due to faulting.

Seams

The Carney and Monarch beds are both members of the Tongue River member of the Fort Union formation and both exceed 15 feet in thickness over much of their extent. The Monarch bed occurs nearly 100 feet above the Carney bed and is the thickest coal in the field. The Monarch bed is thick at the following locations: (1) T57N, R85W, SE ¼ of section 23 - 18 feet, near center of section 25 - 29 feet, NE ¼ of section 26 - 18 feet; (2) T57N, R84W, SE ¼ of section 19 - 29 feet, near SE corner of section 19 - 34 feet, NE ¼ of section 9 - 18 to 20 feet. The Carney bed equals or exceeds 15 feet at the Carneyville mines in Carneyville, sections 9, 15, 16, and 17, T57N, R84W, and section 25, T57N, R85W.

Mining Conditions

Dips are generally low and overburden often shallow making much of the field suitable for strip mining. Faulting and folding is of only minor local significance. The thick seams are continuous except where eroded away but thicknesses tend to vary over distance.

Water Resources

The Tongue River, Little Goose Creek, Goose Creek, and Clear Creek are all perennial streams flowing within the boundaries of the field. A number of smaller streams are also present.

Alluvium along streams, clinker deposits, coal seams, and sandstone members of Wasatch and Fort Union formations are all known to contain groundwater for some part of their extent.

Spotted Horse Field

Location

The field includes about 725 square miles in Sheridan and Campbell Counties in northeastern Wyoming adjacent to the Montana state line.

Topography

The topography is made up of flat-topped buttes; long, narrow flat divides, and even-crested ridges, rising steeply 100 - 600 feet above valley bottoms. Two levels of dissected well-defined erosion surfaces occur in the field. The highest surface is in the southern part of the area where altitudes range from 4,450 - 4,660 feet. Elsewhere in the field the lower surface is on high stream divides and flat-topped buttes ranging from 4,000 to 4,250 feet in altitude. For the entire field total relief is about 1,265 feet from a low point of 3,395 feet where the Powder River crosses the state line into Montana, to a high point of about 4,660 feet along the Powder River - Little Powder River divide near the southern boundary of the field.

Lithology

In sequence from surface units down to lowermost thick coal bearing units.

Rock Units	Thickness	Description
Alluvium	0 - 21'	Sand, silt, and clay with lenses of gravel and rubble along main stream valleys.
Terrace deposits	0 - ?	Sand and gravel deposits along and above the Powder River and Clear Creek and on some drainage divides.
Wasatch formation	0 - 700'	Interbedded shale, siltstone, massive sandstone, and coal. Covers large areas in western and southern parts of field and caps divides in north-central part.

Tongue River member of the Fort Union Formation	1200 - 1300'	Friable thick sandstone, shale, and coal beds.

Structure

The most notable structural feature is a series of gentle south-westerly plunging folds which trend about N 25 degrees East in a belt about 8 miles wide across Tps. 56 and 57 N, and Rs. 76 and 77 W. These folds merge into a shallow syncline trending easterly across the northern portion of the field. Dips are generally less than 3 degrees in a southwesterly direction with occasional minor reversals. Dips can be as much as 11 degrees in the vicinity of faults. Faulting is concentrated in three areas in the field: near the northern and southern ends of the fold belt, and in T54N, Rs. 74 and 75 W.

Seams

The coals in the field range from lignite to subbituminous C in rank. The Canyon and Anderson beds of the Tongue River member of the Fort Union formation and the Felix and Ulm No. 2 beds of the Wasatch formation all exceed 15 feet in thickness for some part of their extent in the field. The Canyon bed averages 16.2 feet thickness over an area of 7,163 acres in T57N, R76W. The Anderson bed averages between 15.1 and 19.3 feet in thickness for about 16,049 acres in T58N R76W, T57N R76W, T57N R75W, T56N R75W, T57N R74W, and T56N R74W. The Felix bed averages between 15.8 and 17.6 feet in thickness for about 30,496 acres in T54N R75W, T53N R75W, and T54N R74W. The Ulm No. 2 bed reaches a thickness of 22 feet in section 27, T53N R74W, but is of small areal extent in thicknesses over 15 feet.

Mining Conditions

Dips are generally in the vicinity of 3 degrees or less although they may exceed that or change direction in proximity to folds of faults. Much of the coal in the field is under shallow overburden and therefore strippable. Some of the thick seams are however, under overburden depths greater than 200'. An example is the Anderson bed in the northwestern portion of the field.

APPENDIX B

BIBLIOGRAPHY OF LITERATURE REVIEWED

Adam, R. French Thick Seams Mining Practices. The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, Symposium on Thick Seam Mining by Underground Methods, September, 1976, pp. 41-50.

Adam, R. Thick Seam Mining by Underground Methods. Symposium on Thick Seam Mining by Underground Methods, Central Queensland Branch, Australasian Institute of Mining and Metallurgy, September, 1976, pp. 41-50.

Adyalkar, P.C., and K.R., Srinivasan. Role of Hydrogeology in Coal Mining Near Chandrapur in Maharashtra, India. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, p. 1.

Annen, G. Water-Management and Hydraulic Engineering in the Rheinisch-Westfaelisch Coal Mining Region. Proceedings of the International Symposium on Fossil Fuel Production and Water Resources, Paper 3, Duesseldorf, Federal Republic of Germany, September 1976, 16 pp.

Baeckstrom, L, L. Carlsson, A. Carlstedt, and A. Hornsten. Influence on the Groundwater Conditions in a Multilayered Aquifer System by Alum-Shale Mining. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 17-26.

Banerjee, S.P., and R.S. Shylienger. Mine Drainage Problems in Indian Coalfields, With Special Reference to the Problems in Jharia Coalfield. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 27-44.

Bewers, C., and K. Wardell. Recent Research in Mining Subsidence. Transactions, Institute of Mining Engineers, 114, 1954-55, pp. 223-244.

Biron, C., and E. Arioglu. Design of Reinforced Artificial Roof of the Thick Lignite Seam for the Soma Mine of Turkey. J. Mines, Met. Fuels, v. 26, No. 2, February 1978, pp. 79-85.

Bise, C.J., R.V., Bamani, and R. Stefanko. Underground Extraction Techniques for Thick Coal Seams. Mining Engineering v. 29, No. 10, October 1977, pp. 35-40.

Black, R.C. The Influence of Structure on Underground Water Pre diction and Occurence at Rokana Mine, Kitwe, Zambia. Water Mining and Underground Works: SIAMOS - 78, Granada Spain, 1978, pp. 45-60.

Bonell, R.A. UK Longwalls, A Review of Strata Control Experience and Current Trends. Proceedings of the Sixth International Strata Control Conference, Paper 25, Baniff, Canada, 1977.

Brauner, G. Subsidence Due to Underground Mining, Part 2, Ground Movements and Mining Damage. BuMines IC 8572, 53 pp.

Broms, B.B., and A. Fredrickson. Land Subsidence in Sweden Due to Water-leakage into Deep-lying Tunnels and it's Effects on Pile Supported Structures. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976.

Buck, W.A. Geological Environment in Relation to Longwall Operation in the U.S.A. Mining Engineer (London), 137(199) February 1978, pp. 363-371.

Buntain, D. Longwall Growth in the U.S. May Depend on How Well Subsidence is Controlled. Coal Mining Process, v. 13, No. 12, December 1976, pp. 71-74.

Cairney, T., and L. Hamill. Interconnection of Surface and Underground Water Resources in Southeast Durham. J. Hydrol. v. 33, No. 1/2, 1977, pp. 73-86.

Caldonazzi, O. Possibilities for Using Process Computers in Open Cast Mine Drainage. Neue Bergbautech, v. 2, February 1978, pp. 101-104.

Chih-Keui, C., and C. Chang-lin. The Exploitation and Control of Karst Water in Coal Measures, Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 111-124.

Clarke, A.M. Some Structural, Hydrological, and Safety Aspects of Recent Developments in South-East Durham. The Mining Engineer, December 1962.

Corbett, R.G. Effects of Coal Mining on Ground and Surface Water Quality, Monongalia County, West Virginia. The Science of the Total Environment, v. 8, No. 1, July 1977, pp. 21-38.

Deutscher Verband Fuer Wasserwirtschaft, E.V. Proceedings of the International Symposium on Fossil Fuel Production and Water Resources, Duesseldorf, Federal Republic of Germany, September, 1976, 470 pp.

Dierks, H.A., W.A. Eaton, R.H. Whaite, and F.T. Moyer. Mine Water Control Program, Anthracite to Region of Pennsylvania: July 1955 - December 1961. BuMines IC 8115, 1962, 63 pp.

Dunrud, C.R. Some Engineering Geologic Factors Controlling Coal Mine Subsidence in Utah and Colorado. U.S. Geological Survey Professional Paper 969, 1976, 39 pp.

Dunham, R.K. Thick Seam Mining: A Review of the Methods. World Coal, v. 4, No. 10, October 1978, pp. 24-27.

Edgar, J. Thick Seam Mining as Practiced at Westfalen Colliery, QLD. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 15-19.

Enslin, J.F., R.J. Kleywegt, J.H.T. Beukes, and J.F. Gordon-Welsh. Artificial Recharge of Dolomitic Groundwater Compartments in the Far West Rand Gold Fields of South Africa. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 495-506.

EDAW, Inc., and Earth Sciences Associates. Environmental and Economic Effects of Subsidence. LBL-8615, GSRMP-1, UC-66e, DOE Contract W-7405-ENG-48, May 1979.

Farmer, I.W., and P.B. Attewell. Similarities Between Ground Movement Around Soft Ground Tunnels and Longwall Mining Excavations. Mining Engineer (London), No. 172, May 1975, pp. 397-403.

Fernandez-Rubio, R., and A. Pulido-Bosch. Hydrological Problems Affecting the Exploitation of the Peat Bog at Padul (Granada, Spain) Preliminary Study, Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 125-132.

Fenk, J. Modeling of Small, Localized Surface Subsidence. Neue Bergbautech., v. 7, No. 6, June 1977, pp. 414-417.

Fissgus, S. Winning Thick Seams in the Rumanian Coal Industry. Glueckauf, v. 114, No. 19, October 1978, pp. 852-854.

Foster, S.S.D., and M. Price. British Examples of a Hydrogeological Approach to the Evaluation of Drainage Problems in Subsurface Engineering. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 409-427

Frank, H. Lining of Open Water Channels with Polyethylene Sheets. Neue Bergbautech, v. 3, March 1978, pp. 175-176.

Gentry, D.W., and J.F. Abel. Rock Mass Response to Mining Longwall Panel 4N, York Canyon Mine. Mining Engineer, v. 30, No. 3, 1977, pp. 273-280.

Ghose, A.K. Design of Support Systems for Future Longwall Faces-An Overview. J. Mines, Met. Fuels, v. 24, No. 5, May 1976, pp. 141-147.

Gloe, C.S. Land Subsidence Related to Brown Coal Open Cut Operations, Latrobe Valley, Victoria, Australia. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 399-407.

Goszsz, A. Formation of Fractures in the Main Roof in the Vicinity of a Working Face, in the Light of Investigations Carried Out by the Geophysical Electrical Resistance Method. Przegl. Gorn., v. 33, No. 9, September 1977, pp. 397-402.

Greenfield, R.J., P.M. Lavin, and R.R. Parizek. Geophysical Methods for Location of Voids and Caves. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 465-484.

Gulati, A.K., and A.K. Singh. Scheme of Developing Seams Below Water-logged Workings. J. Mines Met. Fuels., v. 25, No. 1, January 1977, pp. 3-8.

Hams, A.H. A Case for Coal Mining Research in Australia. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 51-59.

Harrison, C. Mining the Thick Seams of the South Maitland Coalfield, N.S.W. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 1-13.

Holzer, T.L. Ground Failure in Areas of Subsidence Due to Ground-Water Decline in the United States. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 423-433.

Hrastnik, L. Problems of Determining the Safe Thickness of Impermeable Clay Layers Between Coal Seams and Water-Bearing Sand Layers in the Hanging Wall. Rudarsko-Metalurski Zbornik, No. 1, 1971, pp. 45-47.

Huebner, J. Influence of the Floor's Geohydrological Conditions and the Stability of the F-60 Dump in the Nochten Open Cast Mine. Neue Berghautech, v. 8, No. 1, January 1978, pp. 24-28.

Irresberger, H. Roof Control in Longwall Faces. Colliery Guardian, v. 226, No. 4, April 1978, pp. 32, 34-35, 38-40.

Jacenkow, B. A. Balcerzak, W. Gizynski, M. Gnatowski, and A. Pietak. Application of New Chemical Grouts in Strengthening and Sealing of Soils. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 429-440.

Jureczko, J., and E. Skowronek. Investigation by the Tracer Method of the Water Balance When Filling the Gob With Slurries. Przeg. Gornl, v. 33, No. 10, October 1977, pp. 483-487.

Kapp, W.A. The Characteristics of Subsidence Due to Underground Coal Mining at Newcastle, New South Wales. Proceedings of the Second International Symposium on Land Disturbance, IAHS-AISH Publication No. 121, December 1976,

Kenny, P. The Caving of the Waste on Longwall Faces. Int. J. Rock Mech. Min. Sci., v. 6, 1969, pp. 541-555.

Kermerov, A.I., and R.A. Raikh. Predicting Water Inflow in the Kuzbass Pits. Ugol., v. 52, No. 2, February 1977, pp. 58-60.

Kesseru, Zs. Methodology and Application of Analyzing Rock-Water Interaction Endangering Mines. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 637-655.

Kochert, W., and F. Reuter. Grouting Materials - Test Methods and Possibilities for Their Application in Hydraulic Injections. Neue Berghautech, v. 8, No. 1, January 1978, pp. 13-17.

Konstantynowicz, E., T. Bromek, T. Pilat, E. Posylck, and M. Rogaz. Determination of Safety Pillars for Limiting Water Hazard in Hard Coal Mines. Prace Glownego Instytutu Gornictwa,Komunikat nr 615, Katowice, Poland 1974.

Kullhawy, F.H. Geomechanical Model for Rock Foundation Settlement. J. Geotech., Engineering Division, Am. Soc. Civ. Eng., v. 104, No. 2, pp. 211-227.

Kumar, R., and B. Singh. Mine Subsidence Investigations Over a Longwall Working and the Prediction of Subsidence Parameters for Indian Mines. Int. J. Rock Mech. Min. Sci. and Geomech., Abstr., v. 10, 1973, pp. 151-172.

Lofgren, B.E. Hydrogeologic Effects of Subsidence, San Joaquin Valley, California. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 113-123.

Lojas, J., A. Kidybinski, and Z. Hladysz. Working the Lower Lift of a Thick Seam Under the Caved Debris Reconsolidated with Waters from Drainage of Overburden Strata. Sixth International Strata Control Conference, Baniff, Canada, September 1977, pp. 1-10.

Londong, D. Principles for the Planning and Design of Drainage Pumping Stations in Areas of Mining Subsidence. Proceedings of the International Symposium on Fossil Fuel Production and Water Resources, 20 p.

Maung, H.M., and S.P. Banerjee. Investigation into Strata Behavior Around an Experimental Longwall Caving Face in Jharia Coalfield. J. Mines, Met. Fuels, v. 24, No. 9, September 1976, pp. 283-289.

Mohr, H.F. Influence of Mining on Strata. Mine and Quarry Eng., v. 22, No. 4, 1956, pp. 140-152.

Moscnyi, E. Influence of Ground Subsidence Due to Mining on River Regime and Scale Model Experiments. Proceedings of the International Symposium of Fossil Fuel Production and Water Resources, Paper 18, 1976.

Nakajima, S. Thick Seam Mining Techniques in Japan. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 21-40.

Narasimham, T.N., and P.A. Witherspoon. Numerical Model for Land Subsidence in Shallow Groundwater Systems. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 133-143.

National Coal Board. Subsidence Engineers' Handbook. National Coal Board Mining Department, 1975, 111 pp.

Neate, C.J., and B.N. Whittaker. Influence of Proximity of Longwall Mining on Strata Permeability and Ground Water. 20th U.S. Symposium on Rock Mechanics, Austin, Texas. June 4-6, 1979, pp. 217-224.

Newton, J.G. Induced Sinkholes - A Continuing Problem Along Alabama Highways. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 453-463.

Nishida, T., and K. Goto. Damage to Irrigation Pond Due to Mining Subsidence. Land Subsidence, Proceeding of the Tokyo Symposium, 1969, pp. 496-501.

Nithack, W. The Future of Thick Seam Mining - A European View. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 83-92

Oitto, R.H. Three Potential Longwall Mining Methods for Thick Coal Seams in the Western United States. BuMines IC 8792, 1979, 34 pp.

Orchard, R.J. Surface Effects of Mining - the Main Factors. Transactions Institute of Mining Engineers, 116, pp.942-955.

Orchard, R.J. The Control of Ground Movements in Undersea Workings. The Mining Engineer, v. 28, No. 101, Part 5, 1969, pp 259-273.

Pampeyan, E.H., and T.L. Holzer. Earth Fissures and Localized Differential Subsidence. U.S. Geological Survey Open-File Rept. 79-51, 1979.

Peters, T.W. Mine Drainage Problems in North Derbyshire. Mining Engineer (London), v. 137, No. 200, March 1978, pp. 463-473.

Piske, G. Problems to be Solved by the Brown Coal Industry in Geology and Drainage. Neue Berghautech, v. 2, February 1978, pp. 67-69.

Poland, J.F. Land Subsidence Stopped by Artesian-Head Recovery, Santa Clara Valley, California. Proceedings of the Second International Symposium, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 124-132.

Puzrup, H. Coal Mining and Water Economy in the Ruhr. Proceedings of the Internationsl Symposium on Fossil Fuel Production and Water Resources, Paper 28, 24p.

Roll, R.J. Effect of Subsidence on Well Fields. Journal of American Water Works Association, v. 59, No. 1, 1967, pp. 80-88.

Ropski, S., and R.D. Lama. Subsidence in the Near-Vicinity of a Longwall Face. Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., v. 10, 1973, pp. 105-118.

Sadykov, N.M., and V.Y. Setkov. Probability, Statistical Indices of Sudden Roof Subsidences. Sov. Min. Sci. (English Translation), v. 14, No. 2, March 1978, pp. 195-200.

Saxina, N.C., S. Samanta, K.P. Mukherjee, and B. Singh. Strata Control Investigations at Caved Longwall Faces with Special Reference to the Faces at Moonidih Project. Journal of Mines, Metals, and Fuels, March 1978, pp. 109-130.

Schlick, D.D., R.G. Peluse, and K. Thirumalai. U.S. Coal Mining Accidents and Seam Thicknesses. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 61-74.

Schlottmann, A.M. Environmental Regulation and the Allocation of Coal: A Regional Analysis. Tennessee University, Knoxville (USA), Appalachian Resources Project. p. 286.

Schmieder, A. Forecasting the Rates of Water Inflowing Into Mines, Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 511-534.

Schmieder, A. Water Control Strategy of Mines Under Strong Karstic Water Hazard. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 535-552.

Schumann, H.H., and J.F. Poland. Land Subsidence, Earth Fissures and Groundwater Withdrawal in South-Central Arizona, U.S.A. Institute of Scientific Hydrology Proceedings: Reading Symposium on World Water Balance, July 1970.

Schwarz, H. Requirements on Water Barriers and Their Application in the Brown Coal Industry. Neue Berghautech, v. 2, February 1978, pp. 106-108.

Sikora, W. Methods for Working Thick Seams and Research on Increasing Their Effectiveness. Symposium of Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 93-106.

Singh, T.N., and B. Singh. Load and Convergence Measurements in Worked Out Areas in Mines - A Critical Reveiw. Journal of Mines, Metal, and Fuels, v. 19, No. 1, January 1971, pp. 7-21.

Singh, T.N., and B. Singh. Strata Movement Around Workings in a Massive Formation - Equivalent Material Model Investigation. J. Mines, Met., and Fuels, v. 20, No. 9, September 1972, pp. 267-274.

Singh, T.N., and B. Singh. Model Studies of Strata Movement Around a Longwall Face. J. Mines, Met., Fuels, v. 25, No. 2, February 1977, pp. 39-43.

Singh, T.N., and B. Singh. Caving of a coal Seam Under Kamptee Aquifers of India. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 657-673.

Sovinc, I. Geotechnical Aspects of Longwall Face Caving. Proceedings of the Third Congress of the International Society for Rock Mechanics, v. II, Part B, 1974, pp. 1096-1107.

Stefanko, R. Coal Mining in the U.S.A. Rough Draft of a Report Sponsored in Part by Hittman Associates, Inc., Electric Power Research Institute (EPRT), and the Mining Enforcement Safety Administration (MESA), pp. 35-42.

Stringfield, V.T., and J.R. Rapp. Land Subsidence Resulting from Withdrawal of Groundwater in Carbonate Rocks. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 447-452.

Thomas, E.G. Thick Seam Underground Coal Mining By a Slice and Fill Method. Symposium on Thick Seam Mining by Underground Methods, The Australasian Institute of Mining and Metallurgy, Central Queensland Branch, September 1976, pp. 75-81.

Thomas, J.L. An Introduction to Mining-Exploration, Feasibility, Extraction, Rock Mechanics. Holstead Press, a Division of John Wiley and Sons, Inc., Third Ave., New York, N.Y. 10016, 1978.

Thurman, A.G., V. Straskraba, and R.D. Ellison. Development of a Ground Water Hazard Map For an Underground Coal Mine. Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978.

Voight, B., and W. Pariseau. State of Predictive Art in Subsidence Engineering. J. Soil Mechs. Found. Eng. Div. Amer. Soc. Civ. Engrs. v. 96, 1970, pp. 721-750.

Wall, C.F. A Geophysical Method of Indicating Relative Sinkhole Susceptibility. Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, IAHS-AISH Publication No. 121, December 1976, pp. 485-493.

Wardell, K. Ground Subsidence and Control. Mining Congress Journal, January 1969, pp. 36-42.

Wardell, K. The Effects of Mineral and Other Underground Excavations on the Overlying Ground Surface. Symposium on Geological and Geographical Problems of Areas of High Population Density, Washington, D.C., 1970, Proceeding, pp. 201-217.

Weston, J.G. The Determination of Subsidence Profiles by Mathematical Functions. The Mining Engineer (London), April 1978, pp. 493-500.

Whillier, A., and J. van der Welt. Gravity-fed Water Systems in Mines. J.S. Afr. Inst. Min. Metall., v. 77, No. 9, April 1977, pp. 187-192.

Whittaker, B.N., adn D.R. Hodgkinson. Design and Layout of Longwall Workings. Mining Engineer (London), No. 134, November 1971, pp. 79-96.

Whittaker, B.N. Strata Control Developments on the European Continent. Mining Engineer (London), v. 132, No. 153, June 1973, pp. 435, 443.

Whittaker, B.N., and R.N. Singh. Design Aspects of Barrier Pillars Against Water-Logged Workings in Coal Mining Operations. Symposium on Water in Mining and Underground Works, SIAMOS - 78, v. 1, Granada, Spain, 1978, pp. 675-692.

Whittaker, B.N., R.N. Singh, and C.J. Neate. Investigation and Evaluation Studies of Surface and Subsurface Drainage Pattern Changes Resulting From Longwall Mining Subsidence. First International Mine Drainage Symposium, Denver, Colorado, May 20-23, 1979.

Wightman, D. Hangingwall Dewatering at Mulfulira Division of Roan Consolidated Mines Limited, Zambia, Symposium on Water in Mining and Underground Works: SIAMOS - 78, Granada, Spain, 1978, pp. 559-571.

Wilson, A.H. Various Aspects of Longwall Roof Support. Colliery Guardian, v. 226, No. 4, 1978, pp. 50-54.

Wisecarver, D.W. Advantages of Longwall Mining in Western Coal Production. Society of Mining Engineers of AIME Preprint No. 78-F-25, 1978, 7 pp.

Wohlrab, B. Effects of Land Subsidence Caused by Mining to the Groundwater and Remedial Measures. Land Subsidence, Proceedings of the Tokyo Symposium, 1969, pp. 502-511.

Yurgenfel'd, G. Yu., and A.A. Toomik. Drainage of the roof Layers in the Ehstonskii Oil Shale Mines. Ugol., v. 6, June 1978, pp. 35-36.

Zorychta, H., D.W. MacFadgen, and F. Smith. Strata Control Measurements in the Sydney Coalfield. Transactions of the Canadian Institute of Mining and Metallurgy, v. LXX, 1967, pp. 38-48.

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